ON BINOCULAR RIVALRY

PROEFSCHRIFT

ter verkrijging van de graad van Doctor in de Sociale Wetenschappen
aan de Rijksuniversiteit te Leiden
op gezag van de Rector Magnificus, Dr. D. J. Kuenen
Hoogleraar in de Faculteit der Wiskunde en Natuurwetenschappen
ten overstaan van een Commissie uit de Senaat
te verdedigen op woensdag 30 juni 1965
te 14.00 uur

door

W. J. M. LEVELT
geboren te Amsterdam

TE ASSEN BIJ
VAN GORCUM & COMP. N.V. - DR. H. J. PRAKKE & H. M. G. PRAKKE

PROMOTOR: PROF. DR. J.P. VAN DE GEER

THIS THESIS IS ALSO ISSUED AS A REPORT OF THE INSTITUTE FOR PERCEPTION R.V.O.-T.N.O., SOESTERBERG, THE NETHERLANDS

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CHAPTER I

INTRODUCTION

§ 1. The problem

The term 'binocular rivalry' has been used to cover a large group of heterogeneous phenomena. All they have in common is that they are produced by stimulating the two eyes by patterns which are sufficiently different to make fusion impossible. Rivalry, then, is what the subject perceives in the non-fusion situation. Therefore, the meaning of rivalry is dependent upon the meaning of fusion.

The concept of fusion has a certain phenomenological clarity. In normal vision we are aware of only single objects, in spite of the fact that each object produces two retinal images. This fused state can be disturbed by squinting a little, which gives rise to two more or less superimposed 'half-images'. Nevertheless much controversy exists as to the exact meaning of fusion. For instance, since Du Tour (1760) rivalry has been used as an argument for the thesis that every point of the visual field is only perceived with one eye. If the latter is the case, the term 'fusion' seems to be not very adequate, since it implies some unification of the two excitations, whereas in fact no such unification is taking place. On the contrary, if one excitation is operative, the other one is inhibited, or suppressed.

Whichever of the two hypotheses is correct, a number of basic mechanisms of binocular interaction can be inferred by presenting the eyes with non-corresponding stimuli. Various phenomena may be produced in this way. It appears that one stimulus may suppress the other one; sometimes the stimuli may alternate, one only being perceived at a time. In other conditions the stimuli are simply mixed to form some average impression. The effects of suppression and alternation are visible in the classical orthogonal grids pattern of Fig. 1.

Through a stereoscope this stimulus pair does not produce the impression of a stable pattern of crossed bars, but is more like an ever changing mosaic in which parts of either stimulus are present. One never has the impression of a real crossing of bars. At any instant one

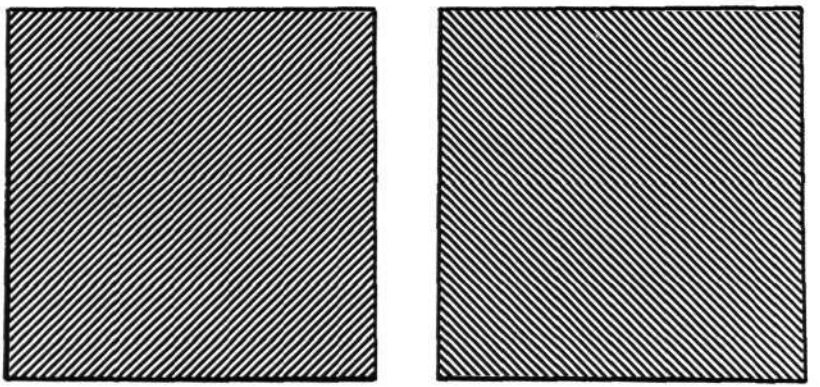


Fig. 1. The orthogonal grids pattern for demonstration of binocular rivalry.

of them is dominant at the point where two bars should cross. We might say that the eyes when presented with such non-fusing patterns relinquish their secret laws of interaction. It is the aim of the present study to find out what kind of interaction mechanisms are at work when the two eyes are simultaneously stimulated by different stimuli.
Non-fusion of stimuli may take place in a number of ways. A non-correspondance of patterns may exist as in Fig. 1. However rivalry may also occur in the case of equal patterns, for instance when they have distinct differences in luminance or colour.
In this chapter, the problem of binocular rivalry will be introduced in two ways. First, the limiting conditions for the appearance of rivalry will be reviewed. This is equivalent to a discussion of the limits within which fused impressions can be obtained. Secondly, a short account of some explicit theories of rivalry will be given. This is not a complete review of the literature on rivalry; it is only meant to show the divergent lines of argument which have been advanced in this area. Other references will come up for discussion throughout this study, where relevant.

§ 2. The limits of fusion and rivalry

It is essential for the appearance of binocular[1] rivalry that it is impossible to fuse the two half-images. They may be non-fusible with

[1] We use the term 'binocular rivalry' rather than 'retinal rivalry', because 'binocular rivalry' agrees better with the terminology in other languages (German, French, Dutch).

respect to contour, brightness or colour, or any combination of these. We shall discuss these features separately.

Contours. The limiting condition for fusion seems to involve the Panum area. It is not necessary for two contours to fall on exactly corresponding areas of the two retinas, in order to be seen as one. A small amount of discrepancy is tolerated. This defines so-called fusional areas or Panum areas. The angular extent of these areas in both the horizontal and vertical direction has often been measured: the Panum area is smaller in the fovea than in the periphery. Ogle (1950) finds for foveal fusional areas a horizontal extent of about 6-8 min of arc. In Chapter V we shall come back to this. Panum's area will then be related to data on rivalry. We shall also deal with an exception to the rule of Panum areas, which is that an image in one eye cannot be fused with its negative in the other eye, as for instance in response to the stimuli in Fig. 2. There is a *horror fusionis* as Linschoten (1956) called it, between contours of inversed contrast. This is most distinct for boundary figures (comp. Fig. 36b).

Brightness. Two stimuli which differ only in brightness can be fused as long as the contrasts are not reversed, and as long as the brightness difference is not too large. With large brightness differences, one of two phenomena may occur. They are usually perceived in succession. First, the brightness of the binocular field concerned changes continuously. The extremes of this variation are the respective brightnesses of the two half-images taken separately. However, a peculiar phenomenon may appear, the effect of lustre. The brightness impression is stable, but the field has the appearance of polished metal. This effect was first described by Dove (1851). A further discussion of the lustre effect is given in Chapter V. The laws determining binocular brightness impression, when monocular fields of unequal luminance are presented, are studied in Chapter III. These laws are important keys for the understanding of binocular rivalry.

Colour. After the first experiments on binocular colour mixtures by Haldat (1806) a vivid discussion arose about the question whether it is possible to produce a stable binocular mixture of two different colours. The Hering-Helmholtz controversy was heated on this point. Hering certified to having seen binocular colour mixtures of a variety of colours. Helmholtz on the contrary, insisted that it is impossible to produce any binocular colour mixture, and that one of the two colours only is seen at the same time. He supported his case by a number of ingenious experiments, from which he was able to attribute all known

cases of binocular mixture to after-images and simultaneous contrast (Helmholtz 1866). Nevertheless, since Helmholtz, a number of authors claimed to have produced the phenomenon under certain circumstances. Among them, we mention Hecht (1928). He looked at a white piece of cardboard, through two different Wratten filters, a red and a green one. The middle of the cardboard appeared yellow under these conditions. Prentice (1948) repeated Hecht's experiments using better filters, in order to answer criticism, made as to the band width of Hecht's filters, but found the same result. Long exposure times seemed to stabilize the impression. Recently the conditions for binocular colour fusion were studied systematically by Thomas, Dimmick and Luria (1961). They found optimal conditions for fusion at exposure times of 5-10 sec; furthermore a small uniform stimulus field (2.5°) should be used, preferably against black background and with equal luminance of the two stimuli. They were able to produce nearly 100% occurrence of colour mixture under these circumstances. Their careful study indicates that the binocular mixture matches perfectly with a monocular mixture of the same components using equal shares. Therefore the problem is not now whether binocular colour mixtures can be obtained but, as Osgood (1953) remarks, why they are so difficult to obtain. Our study however deals with binocular colour interaction only incidentally, since our main concern is contour and brightness interaction.

Contour, brightness and colour. Contour, brightness and colour fusion are not independent. For instance, it has been known since Meyer (1855) that a monocularly presented contour introduces a part of its surroundings to the binocular image. Such a contour is always surrounded by a nimbus of the brightness and colour of its own background. Brightness fusion is dependent upon the particular contour configuration in the two fields. Specifically, with contoured fields it is impossible to obtain stable brightness fusion if there is no fusion of contours as well. On the other hand, fusion of contours does not guarantee a stable brightness impression, nor does it exclude colour rivalry. This is the subject of Chapter IV; we shall than show that this gives us another key for the explanation of binocular rivalry.

As a criterion for the existance of rivalry one sometimes uses the impossibility to obtain a depth impression from disparate images (Treisman 1962, Julesz 1963). This criterion is based on the assumption that non-fusion of contours prevents the possibility of depth perception. However this assumption is not entirely valid. There are

clear instances of situations combining rivalry and stereopsis. The classical stimulus pattern is the example of Helmholtz pictured in Fig. 2. Although the contours do not fuse, and the brightness impression is quite labile, depth can be perceived from the stimulus pair.

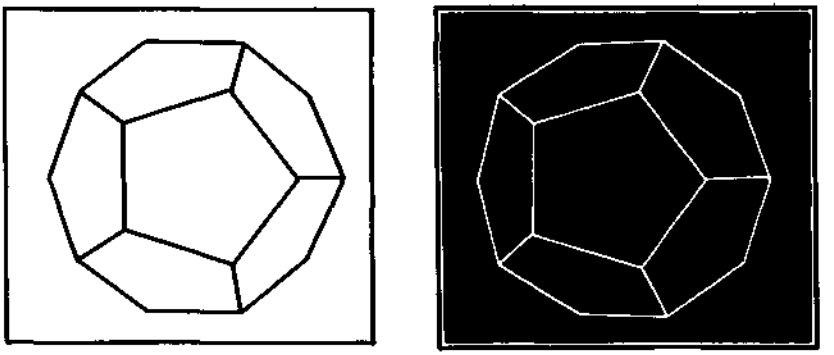


Fig. 2. Depth perception is possible, in spite of non-fusion of contours (after Helmholtz).

Moreover, Ogle (1959) showed that an impression of depth remains possible, even when the disparateness of the stimuli exceeds Panum's area. The character of the depth impression, then, changes from patent and valid to only qualitative ('farther' or 'nearer'). The limit for stereopsis appears to be about three times this fusional area, i.e. 20 min of arc in the fovea.

But the last word has not been said about the relation between rivalry and depth perception. Both Fig. 2 and Ogle's stimuli are line figures. Treisman, however, used borders between dark and bright areas instead. If, in this case, fusion does not occur than depth perception rarely, if ever, is observed. An example of such stimuli is given in Fig. 3b. The depth impression from Fig. 3b is much worse than the one produced by Fig. 3a. This is also true if in both figures the left and the right field are interchanged. But the line-figures of Fig. 3c again produce a good depth impression. However, we mention these effects only in passing, since our main study will not be concerned with problems of stereopsis.

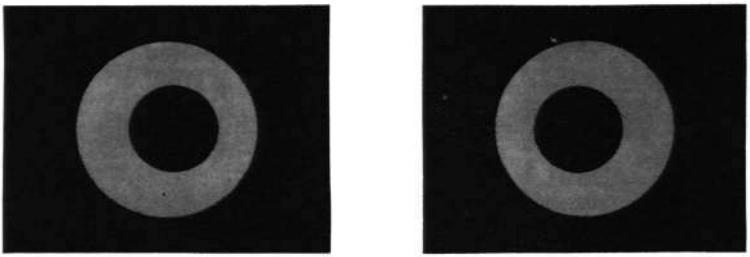
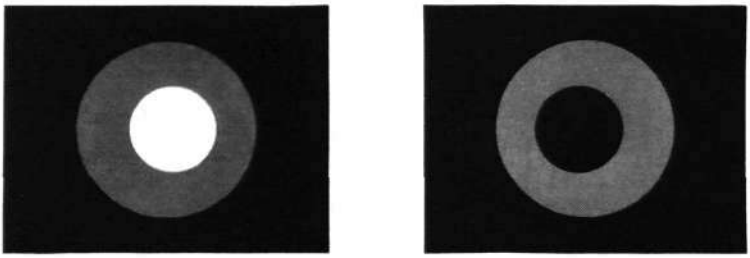
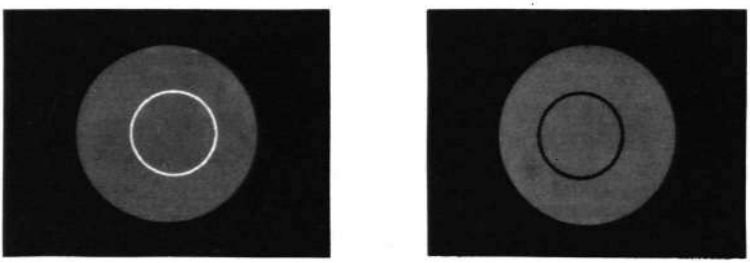


Fig. 3a. Stereoscopically, the central spot appears to be lifted up.



3b. Depth impression apparently does not occur with this stimulus.



3c. Depth impression is again possible with line figures.

§ 3. Attention and set theories

Helmholtz's theory. An example of a 'central' theory of rivalry is the Helmholtz attention theory (1866). It was the first complete theory, and had a large influence upon the later work in the field. The theory is a part of Helmholtz's general theory of depth perception, but for the present we shall restrict ourselves to the following essential points: *a*. That we are normally aware of only one object when perceiving with two eyes is due to experience. Both eyes focus an object in such

a way that its image is on the fovea, with which perception is most acute. Visual experience and continuous haptic control teaches us that the two images refer to one identical object and one gradually learns to see this as one object, as a result of unconscious inference (*Unbewusster Schlusz*). In this way Helmholtz explains how the foveas come to function as corresponding areas, and hence how all other points of the two retinas also become linked to one another in fixed correspondance.

b. In fact, the two visual fields have no organic link at all: fusion is merely a mental act.

c. When the two pictures are dissimilar – contrary to experience – one still perceives them in the same spatial direction, if they are presented to corresponding places. Hence, they are both located in the same area of the visual field, superimposed one upon the other. This is double perception (*Perzeption*). But we are aware (*Wahrnehmung*) then, of dominance of one of them and sometimes of alternations. Thus man has the ability to observe each image in its own right, without being disturbed by the other image, so long as he is able to attend only to the object of one field. In short, there are two perceptions, and attention determines which one will come to awareness.

Helmholtz enumerates some arguments for the total absence of organic fusion of the uniocular pathways.

1. A physical mixture of the grids of Fig. 1 (e.g. produced through a prism) gives an impression which is totally different from the stereoscopic binocular impression. The physical mixture is a case of real fusion, which attention cannot undo, and thus the binocular impression is not a case of real fusion.

2. Making a physical mixture of the images of a printed page and a homogeneously illuminated field (by means of a prism), the letters become unreadable when the luminance of the illuminated field is sufficiently high. This is however never the case when the printed page is presented to one eye, and the homogeneous field to the other. The text then always remains readable.

3. The alternation in the situation of rivalry can immediately be stopped by 'mere mental means', by which attention can be controlled. Examples are –in Fig. 1 – counting bars in one field, distance estimation in one field etc.

4. Faint contours (low contrast) presented to one eye can be seen, even if the other eye is presented with a strong pattern.

Nevertheless Helmholtz admits that all kinds of stimulus factors may

influence the rivalry process. He gives several examples: a relatively lowly illuminated stimulus tends to be dominated by a brighter one, the familiar, ordinary impression tends to be preceived; contours are almost always dominant. The dominance of well-known impressions (trees, faces) is due to experience. This is also true of contour dominance. We are accustomed to the fact that most information is normally to be found at the contours. Helmholtz does not believe in such arguments as that contours produce strong retinal excitations or induce physiological contrast.

Evaluation of Helmholtz's theory. There is no need to argue that attention theories in Helmholtz's sense are infertile in psychological theory construction. This standpuint has already been fully presented (Rubin 1926, Linschoten 1956, Sanders 1963). Linschoten summarizes the criticisms in noting that the 'focussing of attention' can never explain why a particular stimulus is perceived. The next question immediately becomes: 'what determines attention', and so we come back again to stimulus factors. Attention theory is only a theoretical escape mechanism. This also appears to be the weakness in Helmholtz's reasoning. As an example his arguments for the non-existance of sensorial fusion may be reviewed.

His first argument (Fig. 1) implies that a sensorial fusion, as a physical mixture through a prism has to be stable and summative. However there is no reason why this should be true. Why should binocular sensory interaction not be inhibitive and unstable?

The second argument is similar. It only says that binocular fusion seemingly has different rules from those of the fusion of images superimposed in one eye. It does not deny the existence of binocular sensory interaction, it only questions what the exact interaction rules are.

The third argument is quite instructive. Alternation may be stopped by 'mere mental means'; counting is an example. But by counting, the eye is moved perpendicularly to the bars, and as a consequence many more on-off signals are produced in the retina of the 'counting eye'. This may be a reason why the grid under concern becomes more dominant. The way in which other 'mental means' achieve their objects is probably less clear[1], but this example suffices to show the insufficiency of Helmholtz's dualistic reasoning.

[1] Some of these physiological 'means of attention' in rivalry were examined by Fry (1936). By excluding the possibility of similar stimulation he was able completely to eliminate the effect of instructions.

The fourth argument (visibility of faint stimuli) is a combination of arguments 2 and 3. A faint stimulus is not drowned by a strong one, says the argument. But why should not one think of sensory reasons for this as well?
Helmholtz took a position similar to that of the English empiricists. He was convinced that most elementary sensory phenomena originate from experience. This would not only produce dominance of contours (contours get 'prior entry' due to experience), but also retinal correspondance. Whereas, in our opinion, Helmholtz's attention theory is an untestable formulation of this experience theory of perception, the assumption of experiential determination is not untestable in principle. But as it is, evidence is accumulating against Helmholtz as far as binocular interaction is concerned. Corresponding areas of the retinas are anatomically linked in the striate cortex of the cat (Hubel and Wiesel 1962); this is presumably not due to experience, since correspondance can also be found for retinal regions which are never actually used for stereoscopic vision (the extreme nasal part of the visual field of one retina, and the extreme temporal part of the other visual field) (Ogle 1950). Moreover contours appear to be enhanced in the retina by lateral inhibition (Marshall and Talbot 1942), whereas the cortical effect of diffuse stimulation is relatively small (Hubel and Wiesel, *loc. cit.*).

New - Look. Recently, the problem of experience and rivalry again arose in another form, namely in the spirit of what has been loosely called 'New-Look'-movement. The New-Look psychologists had their main interest in the problem of the relations between perception and personality. In a large number of perceptual situations the rôle of experience and set was tested. The first author using binocular rivalry in this area was Engel (1956). His subjects were presented with two photographs of human faces under a stereoscope. One of them was upright, the other one inversed. Subjects had to say which was dominant, and it was found, most frequently, to be the upright face. In this and in the other New-Look situations a complicated mixture of two stimuli is presented in what is generally a recognition task. Recognition thresholds are undoubtedly dependent upon experiential factors and set, as is for instance verbal codability (Fryda and Van de Geer 1961). But the results of Engel's experiments and the other New-Look work on binocular rivalry have little to do with this particular (i.e. binocular) means of stimulus presentation. For instance, if

he had used a superimposed projection of the two photographs as a control stimulus, he would presumably have found the same result. One doubts that the results of these experiments are peculiarly relevant to the problems of binocular interaction, since nothing is said about what particular kind of mixture is perceived. The same holds for all other work on binocular rivalry in the New-Look area (Bagby 1957, Beloff and Beloff 1959, Davis 1959, Hastorf and Myro 1959, Wells and Bell 1960, and Van de Castle 1960). New-Look experiments show that perception is not independent of experience and of personality factors. On the other hand it should be noted that each attempt to deny the existence of relative autonomy (Van de Geer 1955) of the perceptual system has led to nothing. As we are interested in the very laws of sensorial pattern interaction in binocular rivalry we shall leave this perception-personality approach aside.

§ 4. *Hering's theory*

In opposition to Helmholtz, Hering was a nativist in the true German tradition (Kant, J. Müller). He was convinced that the binocular system was an innate structure and not a product of experience. Hering's theory of binocular rivalry is connected to his theory of depth perception, just as was Helmholtz's theory. In fact, Hering (1864) starts at the very weak point in Helmholtz's work. He notices that we always have a singular impression in each point of the binocular field. When the eyes are differently stimulated, the brightness or colour impression in one place may be unstable, or alternating, but two brightnesses or colours are never seen at the same time at the same point. They can be perceived one after the other, or some intermediate impression may arise, but we never see their sum or superposition. This is illustrated by a number of examples. One of them may suffice: two equally large discs of different brightnesses on black backgrounds, are fused binocularly. The binocular brightness is always intermediate between the two monocular brightnesses, or at most equal to one of them. Hering concludes that the excitations from corresponding areas are not summative, but that they compete in the binocular field. The result is

'... that, if we call the resulting sensation unity, both retinas have approximately complementary shares in the production of the sensation, i.e. if the contribution of one retina is $\frac{2}{3}$, then the contribution of the other one is $\frac{1}{3}$. If one contributes $\frac{1}{2}$, then the other also contributes $\frac{1}{2}$, and if one gives 1, the other gives 0. Perhaps

we have to assume that, if both retinas are stimulated absolutely equally, they will have equal shares (i.e. $\frac{1}{2}$) in the common visual field.' (*loc. cit.*, p. 310)

This quotation, which is, as we shall show, most important, occurs quite incidentally to Hering's main argument. He does not present measurements to verify his statement, and he never returns to the topic in his later work.

So, Hering states that the binocular impression arises from a mixture of monocular excitations, whereas Helmholtz maintained that any binocular mixture is impossible. In each point of the common field one of the images is absolutely dominant. For Hering this is only the limiting state of mixture. He even calls it a special case, and in order to show the conditions for such a special case, he uses a second strong argument against Helmholtz. When one eye is presented with a homogeneous field and the other one with some contour, this contour and its neighbouring brightness is dominant and the other eye contributes no more than if it were in complete darkness. This absolute and involuntary dominance of contours is presented as an argument against attention theory. No subject is able to ignore the contour in this stimulus situation, Meyer's law of contour dominance is absolute and without exception in Hering's view. This then, is the important point for Hering's theory of depth perception. He says:

'Binocular depth perception ... is only possible through retinal rivalry and the victory of contours'. (*loc.cit.* p. 315)

For all localization of images is connected with contours. Their dominance is, at the same time, a 'victory' of their depth values (*Tiefenwerthe*), by which – according to his theory of depth perception – localization in depth becomes possible. Suppression of contours, which is possible at will according to Helmholtz, would have disturbed this mechanism. Contour dominance therefore seems to be the hard core of Hering's rivalry explanation. To illustrate this type of explanation, we shall select two examples, one of which is most important and original. The other, however, reveals the weakness of Hering's theory.

The first one deals with Fechner's paradox, a phenomenon generally treated in connection with rivalry problems. Fechner (1861) described the following paradoxical observation. An object of some luminance is observed binocularly, but with a neutral density filter before one eye. If this eye is then closed, the brightness of the object increases, al-

though the amount of stimulation is decreased. Hering does not find this observation paradoxical, because as long as we look through the filter, the binocular brightness is somewhere in between the monocular brightnesses. But when the 'filtered' eye is closed nothing is seen with this eye other than the undifferentiated *Eigengrau*, whereas the other eye is still presented with the differentiated image. The homogeneous field of the closed eye is as unimportant for the binocular mixture, as a homogeneous bright field appeared to be. Fechner's paradox is a result of the absence of contours which are visible through the filter, but which disappear by closing the eye.

Hering's second example is less fortunate for him. In his opposition to Helmholtz, Hering pushed his theorem of contour dominance so far, that he denied the possibility of contour suppression in binocular rivalry (in view of his theory of depth values). The well known fact that a contour in the field of one eye can be inhibited by a contour in the field of the other eye was therefore a hard nut for Hering to crack in his later work (1920). He described an experiment (*loc. cit.* p. 240) in which one eye is presented with a vertical border, separating a black and a white field, and the second eye with a similar horizontal border. Hering says that one border is never so dominant that the other is completely suppressed. Both borders are always visible, even near their crossing point. But Hering then considers a number of well known examples, in which complete suppression of contours seems to be the rule. One of them is Fig. 1. It is remarkable that to explain this suppression, Hering resorts to all kinds of particular circumstances which could be responsible. An example of one of his arguments is that successive contrast is induced along the contours by eye movements; this may inhibit the other contour. Another instance is the strong action of the on-effect, and the weakening action of adaptation to a contour.

Evaluation of Hering's theory. The latter 'explanations' leave the theoretical difficulty that – for whatever reason – one contour may be suppressed by another one. Moreover Hering's main example of the intersecting boundaries is not at all convincing. The point is that Hering's theory of depth perception cannot allow contour suppression since both of a disparate pair of contours have to be visible for their 'depth value' to be active. Hence contour dominance is an unquestionable principle in his theory. This is probably one reason why Hering never again referred to his initial statement that all binocular im-

pressions stem from mixture of the two retinal excitations. Absolute dominance of both contours in rivalry cannot be reconciled with a theory which allows for a mixture in which the retinas have complementary shares.

Nevertheless, Hering's summary remarks on binocular mixture according to complementary shares seems to be most important. It should be admitted, on the other hand, that experimental and theoretical difficulties are also connected with this statement. Experimental difficulties, because Hering did not present measurements at this point, and thus we do not know exactly what he meant. His addendum that we perhaps have to assume that the retinas have equal shares if they are stimulated in absolutely equal ways is ambiguous. In the case of absolutely equal luminances of both fields, we can never test this statement, the impression will be the same for equal and unequal shares, then. Or does Hering mean absolutely equal patterns of stimulation in the retinas, which may be of different luminance? He is not explicit on this point. An experiment would have clarified the position. The first theoretical difficulty is: what is the 'share of a retina'? Is it a share of its illumination, or a share of its nervous response? The thesis of complementary shares requires this distinction to be made. The second unsolved theoretical difficulty is: what rules govern the respective shares of the eyes? When are these shares constant and when not? Under what conditions is a stable impression obtained? Hering only mentions the case of stable dominance of contours in one eye, when a homogeneous field is presented to the other eye. These theoretical difficulties, however, are not *a priori* unsolvable, as was the case with Helmholtz's attention theory. Experimentation may throw light on these questions, and improve our understanding of the process of binocular interaction. In Chapters III and IV examples of experimentation along these lines are given.

In conclusion, therefore, Hering's theory appears to be more fertile than Helmholtz's attention theory. Attention, as Helmholtz uses the concept, is the *deus ex machina* which explains each apparent irregularity in the phenomena. But, in addition, the most essential plank of Helmholtz's platform, viz. the large rôle he attributes to experiential factors in binocular vision, appears to be somewhat fragile. Problems of retinal correspondence and contour dominance are dealt with better by Hering's nativistic theory.

§ 5. Gestalt theory

Binocular rivalry does not receive much attention in Gestalt theory. For instance, Koffka (1936) leaves it as a self evident affair; no reference to Gestalt experiments is to be found in his book. We could find only one Gestalt publication on rivalry, a paper by Gellhorn (1924c). This section considers only a part of this physiologist's work on rivalry. His other contributions are dealt with in Chapter V.

Hering's nativism was one of the most important breeding grounds for Gestalt psychology. Gellhorn himself proposed to test Hering's visual theories in the area of retinal rivalry. But from Gellhorn's work it seems rather likely that he did not know Hering's work on binocular interaction.

Gellhorn tried to find physiological explanations wherever possible (see Chapter V), but he stressed the importance of using the new methods of experimental psychology, if some aspect of the phenomena remained physiologically unsolved. Two such psychological phenomena are treated in his paper.

a. When a figure is presented to one eye and a homogeneous field to the other eye, the figure is permanently dominant. Gellhorn did not know of contour predominance, as may be concluded from the surprise with which he described the result under concern. He moreover did not refer to Panum's or Hering's work on it. His conclusion was that a Gestalt is dominant in binocular rivalry, and he noticed that this dominance is less strong in the periphery of the visual field. This latter point was also stressed by Wilde (1938).

b. For the situation in which two different Gestalts are presented to corresponding areas of the monocular fields, Gellhorn suggested the rule that it is impossible to see single parts of a Gestalt. A Gestalt is present *in toto* or not at all, nothing in between. The substance of this theory may be exemplified by considering the stimuli presented in Fig. 4.

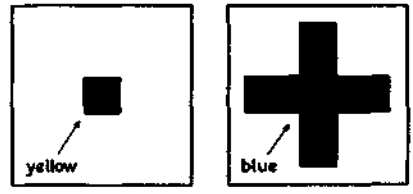


Fig. 4. The yellow square dominates the blue crossing point (after Gellhorn).

Gellhorn noticed that one usually sees a blue cross, except for the crossing point, which appears as a yellow square. Although the blue cross is thus partly visible, Gellhorn said that this is only apparently in contradiction with his theory: phenomenologically the Gestalt of the cross is preserved as a background for the yellow square.

Evaluation of Gellhorn's Gestalt theory. The main point of Gellhorn's theory seems to be that the traditional predominance of contours is replaced by a predominance of Gestalts. But this has not been tested by comparing Gestalts to non-Gestalts. Moreover, there is no necessity to introduce the theoretically ambiguous concept of Gestalt if an explanation in terms of single contours serves as well. Furthermore the reduction of dominance in peripheral vision has nothing to do with binocular interaction, as will be shown in Chapter II. Finally Gellhorn's rule for Gestalt-Gestalt interaction is untestable as a consequence of his lack of definition of terms. And even if we decide to take recourse in Gestalt-background reasoning, we find that it appears also to be invalid, as will be shown by a counter example in Chapter IV.

§ 6. Our program

The aim of this introduction was to place binocular rivalry in the framework of other binocular phenomena such as fusion and depth perception, and to outline the positions taken on rivalry by some classical theories of visual perception.

To understand why apparent perceptual conflict arises when non-corresponding contours are presented to the eyes (as in Fig. 1), two simpler forms of binocular interaction have to be studied. The first is the brightness interaction of a pair of equally patterned, but not necessarily equally luminous stimuli. The second is binocular brightness interaction when a contour is present in one field only. In this latter stimulus situation a special type of phenomenon may arise which has always previously been attributed to binocular interaction, but with insufficient reason. We call this phenomenon 'spurious rivalry'. This effect has to be cleared up before the rest of the program can be started with.

The program, then, is as follows. In Chapter II the confusion in the literature about what we call spurious rivalry is dealt with. In Chapter III, the first mechanism of binocular interaction, which has been labelled 'binocular brightness averaging' is studied. In Chapter IV,

the second mechanism, concerning the effect of a monocular contour, is treated. This has been called the 'contour mechanism'. Its working appears to be so general, that similar effects could also be demonstrated in monocular vision (monocular rivalry, if one wants). In Chapter V the interaction of averaging and contour mechanisms in the situation of rivalry among contours is studied. A model is proposed, which describes the process of alternation of dominances which occurs in contour-contour rivalry. Predictions from the model are tested on data obtained from the literature on alternation and by the author's own experiments. The statistical properties of the model are also described. Finally, the initial problem of § 1, Chapter I about the relationship between fusion and rivalry forms the subject of the concluding section of Chapter V.

CHAPTER II

RIVALRY AND TROXLER'S EFFECT

§ 1. Introduction

In studies on binocular rivalry two quite different phenomena have been demonstrated. The fact that they have never been differentiated has caused much confusion in the literature. The distinction to be made will be between what may be called 'spurious rivalry' and real 'interactive rivalry'. It will be shown that these two types of phenomena are due to quite different types of mechanism.

By interactive rivalry we mean extinction of colour, contour or brightness of the percept from one eye by stimulation of the other eye (see e.g. Fig. 1). Spurious rivalry, however, arises when a homogeneous field is presented to one eye, and some contoured target to the second eye. Although a contour is dominant with respect to a homogeneous field in binocular interaction, this dominance of contours decreases to the periphery of the visual field. One finds, that the target tends to fade away, when viewed peripherally. This fading is generally attributed to the same inhibition mechanism as in interactive rivalry. In our opinion this is incorrect, these two phenomena have to be clearly differentiated. If this is not done, one runs into a number of difficulties. For instance, the fading only takes place for a peripheral stimulus. Does this mean that the mutual inhibition of the eyes changes towards the periphery, e.g. in the sense that weak stimuli are favoured at the cost of strong stimuli? But why then, is the contour-contour type of rivalry rather insensitive to the degree of eccentricity?

The aim of this chapter is to show that these and similar questions are unsolvable, as long as one maintains that the fading phenomena in the contour-homogeneous field rivalry are due to mutual interaction of the eyes. It will be shown that these phenomena arise as a consequence of spontaneous fading of an image in one eye, independent of the stimulation of the other eye. Therefore the term 'spurious rivalry' is used.

Spontaneous fading of an image has been called 'Troxler's effect'.

This effect is the subject of the next section. Authors on binocular rivalry did not recognize the importance of Troxler's effect in some classical rivalry situations. A number of passages from the literature on rivalry will be given as examples of the confusion in this field.
Some aspects of Troxler's effect are discussed in the subsequent section (§ 3). Thereafter the relation of Troxler's effect and spurious rivalry will be discussed (§ 4), chiefly on the basis of Wilde's study on binocular rivalry, which is the most elaborate example of confusion of binocular interaction and Troxler's effect. Some remarks on the localization of Troxler's effect in the visual pathway are presented in § 5 in order to show that there is no coercive physiological reason to expect binocular interaction in Troxler's effect. Finally, in § 6 a situation is considered in which both spurious and interactive rivalry are demonstrable.

§ 2. Spurious rivalry in the literature

Studying the effect of contrast on rivalry between two grids, Roelofs and Zeeman (1917) use as a limiting condition the case of a small grid in one eye and a homogeneous (contrastless) field in the other eye. They notice that the grid is permanently visible in this situation, but only if it is fixated. With parafoveal presentation the grid disappears at moments. Some 'rivalry' occurs, according to the authors. Roelofs (1921) shows later, that a binocular parafoveal stimulus disappears as well. From this he concludes that the fluctuations in binocular rivalry are more or less independent for the two eyes. Whether mutual inhibition plays a rôle in binocular rivalry becomes problematic as a result, but Roelofs does not go into this question.
Gellhorn (1924b) questions whether the 'dominance ratio' of two differently coloured targets presented on corresponding areas of the retinas changes as they are presented more and more to the periphery of the visual field. He defines dominance ratio as the ratio of the total dominance time of the left colour, and the dominance time of the right colour during a 1.5 minute observation period. He expects a change in ratio on the basis of the just mentioned results of Roelofs and Zeeman: Gellhorn hypothesizes that, if a homogeneous field becomes relatively stronger in dominance at the periphery of vision, one may expect similar changes in dominance when two differently coloured targets of unequal 'strength' are presented to corresponding areas. The 'recessive' target should grow in dominance to the periphery. To his surprise

he does not achieve unequivocal results to support his hypothesis, while Roelofs' results were doubtless.

A third example is given by a study of Diaz Caneja (1928). This author questions whether binocular rivalry has to be conceived of as a total reaction of one eye to stimulation of the other eye, or whether it is a kind of partial inhibition such that at moments parts of one field are inhibited by parts of the other field. To investigate this he did the following experiment. One eye was presented with a homogeneous field (black or white), and the other eye with some pattern of points. He found that the fixated point did not disappear at all, whereas points to the periphery tended occasionally to disappear, and this was most marked for the most peripheral stimuli. Although this statement seems to be correct (see Fig. 1), Caneja's experiment is not conclusive on this point. In particular, it is not made clear that the fading in one eye is a result of an inhibitive action of the homogeneous field in the other eye.

Another example is furnished by Crain (1961). Crain considers a statement of Alexander's (1951), which asserts that rivalry only occurs if non-corresponding contours are presented to the eyes. Against this, Crain emphasizes that sometimes a figure presented to one eye is extinguished by a homogeneous field in the other eye. However, with central fixation of the stimulus, this has never been reported by any author. Presumably Crain's observation concerns the fading of a peripheral stimulus in one eye, if the other eye is presented with a homogeneous field. But, it is not sure that this fading is due to binocular interaction, as in the case of rivalry between contoured or structured fields (as in Fig. 1). The patterns of Roelofs and Zeeman, of Gellhorn and of Alexander are of this kind. The second type of stimulus pair comprises a figure in one eye and a homogeneous field in the other eye. This type is used in the studies by Roelofs, Diaz Caneja and implied in Crain's argument. It is the stimulus situation in which spurious rivalry can be observed in the simplest fashion. Our argument is that the figure fading in this situation is spontaneous and has nothing to do with the homogeneous stimulation of the other eye. This spontaneous fading can be explained as Troxler's effect.

§ 3. Troxler's effect

Spontaneous fading of the image has long been recognized; recently it has been called Troxler's effect, after D. Troxler who was the first

to describe the phenomenon (1804). This effect has generally been studied in the following form.

A spot, brighter or darker than the surrounding field is extra-foveally presented. After some time the spot fades and merges into background. Usually it reappears after a while, and the process is repeated again and again, producing the impression of periodic fluctuation of the stimulus. The relative length of the negative phase (the period of absence) increases with the eccentricity of the spot. This effect is not induced by stimulation of the other eye, it occurs also when the spot is observed binocularly, as we will see (§ 5).

The faded image is 'filled in' by the brightness or colour of the surrounding field in the same eye and in a rivalry situation behaves in the same way as a homogeneous field. A non-faded contour on the corresponding area of the other retina will be dominant, then, according to Panum's rule of contour dominance.

A lot of research on Troxler's effect was done around the turn of the century. The effect was studied in connection with the problem of perceptual fluctuation: according to the view of that time, a special kind of attentional fluctuation. A number of workers considered it a consequence of sensorial fatigue. Among them may be mentioned Münsterberg (1889), Pace (1902), Hammer (1905), and especially Ferree (1906). According to Ferree the stimulus fades out due to some local adaptation process in the retina; this explains the importance of eye movements for the reappearance of the stimulus.

Guilford (1927) showed that the return of a faded patch was usually preceded by an increase in the frequency of eye movement. Furthermore he found that a faded point returned, on average, in 1.8 sec when it was presented on another area of the same retina immediately after disappearance. The normal negative phase was 11.6 sec. Stimulation of fresh receptors appeared to be important for reappearance of the image.

The meaning of 'fresh receptors' in this connection is studied by Fry and Robertson (1935), who show that stimulation of new receptors is not sufficient in itself to produce reappearance. A bright spot on a less bright background, visible for 82% of the viewing time, if sharply contoured, becomes permanently invisible if the contours are sufficiently blurred. According to Fry this cannot be due to retinal processes, because no peripheral account can explain how a process in the border receptors of the field can affect the receptors at the centre of the field. Fry concludes that the fading process is governed by

border processes in the retino-cortical paths (His argument against a cortical origin of the effect is given in § 5).
Recently, Troxler's effect was thoroughly studied by Clarke *et al.* Our discussion on the relation of Troxler's effect and spurious rivalry will chiefly be based on Clarke's data as compared with Wilde's data on rivalry. Clarke, as Fry and Guilford, was interested in the location of Troxler's effect in the visual pathway. This aspect of Troxler's effect, as compared with localization in binocular rivalry will be the subject of § 5.

§ 4. A comparison of Wilde's and Clarke's studies

Summarizing a number of studies on rivalry (including Roelofs' and Gellhorn's), Wilde (1938) concludes that the stimuli used are too complicated in structure, to provide a basis for the formulation of laws of rivalry. He, therefore, questions which stimulus condition can be considered the simplest one, and he suggests that it has to be of the following form: one eye is presented with a bright empty field; the other eye with a small black figure (square, disc etc.) on a similar bright background. Thus Wilde makes an unperceived transition from contour-contour rivalry to contour-homogeneous field rivalry, which is in our opinion the situation in which only spurious rivalry can be seen. As a measure for figural strength he uses the time T from the start of the presentation until the moment the figure starts disappearing for the tenth successive time. Initially he uses as his figure a 5×5 mm black square on a white background. It is not possible to determine the visual angle subtended by this square, the luminances of the figures and other physical data. Presumably he used daylight conditions.
Wilde's first finding is a relationship between T and the eccentricity of the square. At foveal presentation of the stimulus, $T = \infty$ (the square does not disappear); towards the periphery the rate tends to stabilization at some value. The T-function is hyperbolic in appearance. He compares this curve with the function of alternation rate obtained in an interactive rivalry situation: a vertical bar to one eye and a horizontal one to the other eye. He gets another result in this situation. Though large individual differences are found, only a slight tendency for the T to increase towards the periphery is found, in contrast to the large phase-shortening effect he obtained in the spurious rivalry condition. He regards his result as a problem, but does not note the essential difference between the stimulus conditions. He lays the difficulty aside, as theoretical conclusions seem to be premature.

In the next experiment Wilde varies the size of the square. He finds that T increases linearly with the total outline of the figure (not with its area). We call this his first law: Figural strength (defined in terms of T) is linearly proportional to contour length. This is in agreement with the results onTroxler's effect, as will presently be shown. At this point Wilde again confuses real and spurious rivalry situations. He mentions an experiment by Allers (1935) in which the stimulus resembles that shown in Fig. 1. Allers substituted a wave pattern for one of the straight bar patterns and found the wave pattern to be more dominant than the bar pattern. He explained this finding in terms of the attention theory: the wave pattern is more interesting. Wilde, however, explains the relative strength of the wave pattern in terms of its greater total contour length. Although he may be correct in this explanation, his own experiments are not sufficiently thorough to justify putting it forward with any confidence. Wilde did not show that his first law has anything to do with binocular interaction, which is surely the case in Allers' experiment.

As the second law of Wilde we denote the fact that not all contours contribute equally to the relationship stated in the first law. It only holds for so-called 'outer contours', not for 'inner contours'. The concept of inner contour is ill-defined, but it is clarified by the following experiment. When a figure, e.g. a square, is divided into two halves and when these halves are shifted apart a little (thus increasing the total contour length), the rate of disappearance does not change, as long as a certain interspace is not exceeded. Furthermore the two parts of the figure appear and disappear together in this situation. The contours bordering the interspace are called 'inner contours' (*Binnenkontouren*). Wilde gives his results in a summary way. He usually gives the data of a characteristic subject. It is therefore not always possible to find trends in his data other than the ones he describes. It seems improbable that inner contours have absolutely no effect on the relative strength of a figure, unless they are to be defined circularly as those contours which have no such effect. The looseness of Wilde's definition leaves him open to the charge of circularity. Some quantitative approach is possible on the results of an experiment in which a black square is replaced by an outline square of equal size. This contour-square does produce a slightly increased T. However, other experiments are conclusive in as much as the law of contour length does not hold any more when fine contour differentiation is introduced within the stimulus figure.

Combining the two laws, Wilde makes precise predictions of T for a contour-square, and a contour-triangle from T_b, the measured time of ten disappearances of each edge of the figure presented alone. The prediction is that $T = \Sigma T_b/2$ (summing the effects of the contours, and deviding by two in view of the ineffective inner contours). This prediction is borne out by the results[1].

With these laws Wilde dissociates himself from Gestalt views. In a further experiment, however, he finds it impossible to escape these views. He now uses a square, a rectangle and a circle of equal outline. The results are very inconsistent for the different subjects. We performed an analysis of variance on his data. The only significant source of variation was Subjects ($p<0.005$). Stimulus conditions appeared to be non-significant. Wilde is not able to infer a clear order of strength for these figures. For lack of other, interpretations of the individual differences, he feels himself bound to accept some Gestalt influence in this situation. However, there is no Gestalt law predicting inconsistencies between subjects.

This short and incomplete treatment of Wilde's experiments suffices to make a comparison between these phenomena of rivalry and Troxler's effect.

In Clarke's study on Troxler's effect (1960) two circular fields were presented monocularly, one central and one peripheral. The central field was of fixed size (1 or 2°) but variable luminance, and was fixated by the subject.The luminance of the peripheral field was variable, either by the subject or by the experimenter. Its size and peripherality (5°, 20°, or 40° in the upper meridian) were varied by the experimenter between sessions.

The procedure was always as follows. The subject adjusted the apparent brightness of the peripheral test field to that of the foveal comparison field (retinal luminance 8000 trol). This was repeated for three short exposures. After this and after sufficient dark adaptation, the test field was presented at the mean luminance of the adjustments. The central field was again of 8000 trol, and therefore both fields appeared equally bright. Now the subject adjusted the luminance of the foveal comparison field, in order to maintain equality of brightness between the fading peripheral patch and the foveal field. This course of adjustment was recorded. The curves, thus obtained, show the decline of brightness of the extrafoveal test patch.

[1] Apart from the data in his table 18, in which a propitious calculation error is made.

This decline is quite characteristic. There is always an initial latency time of 1-2 sec, in which the brightness is constant. After this, the contour fades out apparently, and the brightness quickly decreases within 5-7 sec. If the size of the test field is not too large, and if the test field is sufficiently peripheral, the disappearance becomes complete. Careful fixation is a necessary condition for this. Clarke showed that latency time increases with test field size. The same is true for the adaptation time (the time needed for complete disappearance). The critical field size, just leading to complete disappearance, increases with eccentricity. Clarke presents a graph showing the relation between latency time and log area of the test field. The spread is rather large, but the relation is clearly curvilinear. Wilde's first law predicts a rectilinear relation between outline and adaptation time. To compare with Wilde's prediction we had to transform log area in outline. For this transformation, we did not look for data on total adaptation time in Clarke's curves, because the precise moment of disappearance is very uncertain, but took the time at which a fixed reduction of brightness (1.0 in Clarke's notation) had occurred. In Fig. 5 this fading time for two measurement series is given as a function of test field diameter. These results agree with Wilde's law as well as one could expect in view of the large difference in conditions between the experiments.

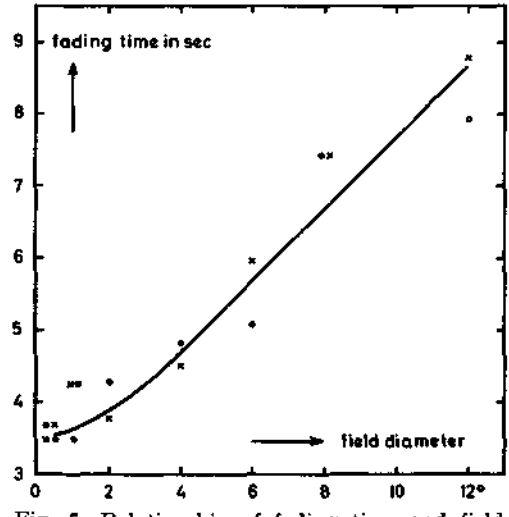


Fig. 5. Relationship of fading time and field diameter in Clarke's data (two measurements series o en x).

Wilde suggested that his 'rivalry' was a boundary effect. Clarke suggests that Troxler's effect is a boundary effect, just as Fry (*loc. cit.*) did. To demonstrate this Clarke substitutes for the homogeneous test field a grid of equal size, and equal total energy. In this situation first the grating structure disappears, leaving a diffuse brightness, which may also fade. But complete disappearance does not usually occur. This is a confirmation of the boundary hypothesis. The problem of the definition of the 'inner contours' arises again here. Have the contours of this experiment to be conceived of as inner contours? As such they should not contribute to the figural strength according to Wilde. By Wilde's loose definition it is not possible to decide on the status of the grid contours in this experiment. As to Wilde's second law, a comparison with Clarke's data seems impossible.

A last comparison is possible as to the effect of eccentricity. Wilde's T stabilized towards the periphery. Degree of peripherality had only substantial effects for small eccentricities of the test spot. Clarke studied three conditions of eccentricity: 5°, 20° and 40°. Using the same measure for fading time as in Fig. 5, we calculated the mean fading times for comparable field sizes at 40° and 20° respectively. The increase in fading time was only 16% from 40° to 20°. However, comparing 20° and 5°-situations, an increase in fading time of 76% appeared. This resembles Wilde's finding, but Wilde gives no data on visual angles, therefore more detailed comparisons are impossible.

A final remark as to the comparability of the stimulus situations of the two studies. Wilde used a black spot on a bright background, Clarke a bright spot on a black background. But Clarke did not achieve essentially different results when he used a black test spot on a bright background as a control.

This comparison of Wilde's and Clarke's data suggests a similarity of the underlying mechanism for the two cases. The only essential difference is the stimulus condition. In Wilde's situation one eye was presented with a homogeneous white field; in Clarke's experiment one eye was covered. It is possible to test in a direct way whether the presence of the homogeneous field introduces essential differences.

Experiment 1

Apparatus. For details of the apparatus used, see Chapter III.

Procedure. One eye of the subject was presented with a white circular test spot, 1° in diameter. It was positioned at 12° in the upper meridian

above a small fixation point. The brightness of the test spot was 1 cd/m², while the background was dark. In the other eye one of two stimuli could be presented: a fixation point on the corresponding place to the first eye's fixation point (fovea), or a 5° circular homogeneous field, which was positioned binocularly concentric with the test spot. The luminance of this homogeneous field was also 1 cd/m². Four conditions were formed by presenting the test spot to the right or the left eye, and by presenting either the homogeneous field or only the fixation point to the other eye. Both eyes looked through circular artificial pupils, 2 mm in diameter.
Each of eight subjects was presented with each condition for 1 minute. He had to push a key, as long as the test spot was invisible. This was recorded by means of a scriptor. The four conditions were given to the subjects according to a 4 × 4 latin square design, with one repetition. The total time of absence of the test spot was calculated for each condition, and expressed as a percentage of the total viewing time (1 minute).

Hypothesis. If the fading of the test spot is produced by an inhibiting action of the homogeneous field in the other eye, one might expect that a large amount of the variance in the results would be due to this variable. However we start with the knowledge that Troxler's effect may play a major rôle in this situation. The question then is, whether a binocular interaction effect can be established at all. The experiment may be conceived of as an indispensable control experiment, omitted by Wilde.

Results. An analysis of variance did not show any effect of the homogeneous field condition (nor of the eye, nor of the eye–field interaction) nor a real tendency in that direction; the mean time of absence with inhibition field was 27.1 sec, without inhibition field 26.5 sec.
The conclusion from this section is therefore, that Wilde's explanation of his own results in terms of binocular interaction has to be rejected. This spurious rivalry is nothing else than Troxler's effect.
Yet Wilde's conclusions on binocular rivalry are adopted by a number of other authors, e.g. by Metzger (1953, p. 248) and by Linschoten (1956), who associates himself with Wilde in his treatment of Allers' experiment (p. 266).
The same conclusion applies to the examples given in § 2. They are all instances of identification of binocular interaction with Troxler's effect.

§ 5. Localization of Troxler's effect and binocular interaction

When a target is presented to one eye and a homogeneous field to the other eye, the fading of the target is an independent process. This does not per se exclude binocular interaction of fading processes, if targets are presented to both eyes. For instance, one could think of synchronization of the fading processes of the two targets. Such a process might interfere with binocular rivalry then.

The question as to whether binocular interaction exists in Troxler's effect is in a way equivalent to the question of localization of Troxler's effect in the visual system. If the effect is produced at a rather peripheral level, binocular interaction in the above sense is not likely to exist. The aim of this section is to show that the latter seems to be the case.

Guilford gave the first data on binocular interaction in Troxler's effect. We noticed (§ 3) that Guilford found a normal negative phase of 11.6 sec. But when the point was presented in a corresponding place to the other eye immediately after fading-out, the mean negative phase was 3.7 sec. If the fading out were due to central adaptation, this strong shortening of the negative phase should not be expected. However, the mean negative phase reduced to 1.8 sec when the stimulus was presented to another area of the same retina immediately after disappearance. This suggests a slight difference between the monocular and the binocular shift. Furthermore, Guilford also found that (under somewhat different conditions) if the stimulus was left upon the first eye, when presenting it to the other eye after disappearance, the mean time for reappearance was 1.9 sec. as compared with 1.2 sec when the stimulus was simply shifted to the other eye after fading.[1] This experiment suggests that the faded image may have a slight inhibitory influence on the formation of the image in the other eye. Hence, one may think of some minor rôle of central adaptation in Guilford's experiments. But other factors may be responsible for this too, e.g. eye movements. However, the main reduction of the negative phase is obtained by presenting the stimulus to fresh receptors.

Fry (*loc. cit.*), studying the fading of a bright stimulus on a less bright background, also indicates that this process is not primarily central. Starting from the measured appearance-disappearance cycle for each eye, he predicts the binocular cycle for the cases of binocular dependency and of binocular independency. He uses a rather rough method of

[1] These mean times are calculated from Guilford's data in such a way that they concern instances, comparable in all respects but the pertinent variable.

prediction, but his results strongly suggest that the processes in the two eyes can be considered as independent. A small interaction, as found by Guilford, does not contradict his results, as he readily admits. Fry supposes the retino-cortical paths to be the locus of Troxler's effect.

Fry shows that Troxler's effect can be produced with a binocular as well as with a monocular stimulus. This explains Roelofs' result (comp. § 2). It also contradicts Wilde's line of thought. According to Wilde the spot fades because of stimulation of the other eye. Rivalry does not occur when precisely the same stimulus is presented to the other eye. Therefore, there is no reason for disappearance in the binocular case. Even if one assumes that two identical stimuli on corresponding places mutually inhibit each other (Verhoeff's theory, see Chapter V, § 6), one would also expect no disappearance in the binocular case. The two images will simply alternate and at every moment one of them is visible, the stimulus is perceptible all the time.

Clarke and Belcher (1962) go into the problem of the localization of Troxler's effect by other means than the former authors. They measured the adaptation time for a test field of low luminance in extrafoveal presentation, and calculate the number of light quanta per sec, striking this part of the retina. Furthermore they estimate the number of photoreceptors in this area. They conclude, that at the end of the measured adaptation time (the moment of disappearance) at most 1/10 of the receptors have absorbed a quantum. Otherwise stated: the test field disappears at a moment in which photoreceptors are being stimulated for the first time. Hence, adaptation of the photoreceptors cannot be the origin of Troxler's effect. This seems quite acceptable, but the authors go further in arguing that Troxler's effect cannot even be localized at the level of the functional units of the retina (receptive fields), but that it is of postretinal origin. This conclusion is drawn from the following experiment. A 1° square test stimulus (1200 trol on a dark ground), at an eccentricity of about 20° in the upper meridian is made to fade out. At the moment of complete fading the subject presses a button, and, at the same time the test patch is displaced with a quick jerk for some distance d. The question now is whether the spot reappears as a consequence of this 'flick'. The authors determine a frequency-of-seeing curve as a function of log d. To get an impression of n, the minimum number of functional units which have to give an 'on'-response in order to produce a reappearance of the image, they try to fit a Poisson cummulative probability function to their data.

For $n = 3$ they find the best estimate. The conclusion is that at least three functional units have to give a response to produce new perception of the test patch. Therefore, Troxler's effect cannot be localized in the functional units of the retina: it has a more central position in the visual pathway.

This conclusion seems premature, however. As the authors state, Poisson statistics only deal with *random* events in a continuum. It is not certain that the responses of the functional units can be conceived of as purely random events. The usually acceptable mathematical simplification cannot be made in this case. It is known that the size of a functional unit is a dynamic quantity, dependent on stimulus energy. The unit is not a fixed, independent structure (comp. e.g. Hartline 1940) It only indicates the range within which stimulus summation takes place. Because of this dynamic aspect of the functional unit, it is most unlikely that a single photoreceptor discharges to the field centre of only one functional unit, in as far as this statement has any meaning at all. Therefore the on-events are in all probability not independent. In that case the statistic used is not appropriate. For the present there seems to be no reason to place Troxler's effect more centrally on the visual pathway than at the level of the functional units of the retina.

Clarke and Belcher hypothesize that it is the same receptive field mechanism that controls visual acuity. This gives them the opportunity to control whether their three functional units of the displacement experiment are really receptive fields. In fact, the receptive field size calculated from this experiment appears to be in good agreement with the visual acuity as determined in a new experiment under comparable conditions. But this agreement is no strong argument. For their calculation of unit-size from the displacement again implies functional independency of these units, and even more injustifiable: non-overlap of these fields.

In conclusion there is no sufficient argument against a receptive field theory of Troxler's effect.

Clarke and Belcher also give information as to the localization limits of Troxler's effect toward the central side of the visual pathway. They proceed to binocular experiments, just as Guilford and Fry did (without reference to their work). They study binocular interaction in Troxler's effect, by determining the absolute threshold for vision in the left eye by means of a small eccentric test stimulus corresponding to the centre of a larger patch of light in the right eye (the conditioning

stimulus) This threshold is determined under three conditions: 1. after occlusion of the right eye (no conditioning stimulus) 2. after disappearance by Troxler's effect of the conditioning stimulus, and 3. after a 30 sec intermittent exposure of the conditioning stimulus. The authors find no significant differences between these three conditions, and conclude that Troxler's effect does not show important binocular interaction. Hence, it has to be localized somewhere in the peripheral pathways.

Although this conclusion agrees with Guilford's and Fry's, it seems that Clarke's experiment does not conclusively exclude binocular interaction for the following reason. Clarke himself states that Troxler's effect is a kind of boundary effect. Therefore binocular interaction might take place as follows: when fading has set in in one eye, a corresponding boundary in the other eye is less likely to be perceived. However, Clarke's test stimulus was smaller than his conditioning stimulus, so that their boundaries did not coincide. The kind of binocular interaction hypothesized could not therefore be shown in Clarke and Belcher's experiment. Nevertheless, it is new evidence in favour of Guilford's and Fry's statements that binocular interaction does not play a substantial rôle.

We performed a small and informal experiment in which we presented the test stimulus of Exp. 1 (under exactly the same conditions), without homogeneous field, to the left eye, the right eye, or to corresponding places of both eyes. The presentation time was 1 minute per condition. The experiment was repeated five times on one subject (W.L.). The mean negative phase occupied 36.2% of the observation time for the left eye ($s = 6.4\%$), and 34.4% ($s = 4.7\%$) for the right eye. With stochastically independent processes the mean negative phase would be $36.2\% \times 34.4\% = 12.6\%$. We found it to be 13.4% ($s = 3.9\%$). This again suggests the binocular independence of Troxler's effect. A certain interaction could be produced by saccadic eye movements, which usually occur together in both eyes.

As possible sites of Troxler's effect Clarke and Belcher suggest the lateral geniculate bodies and the reticular formation. The reticular formation seems an improbable locus to us. The general arousing effect this body is apt to produce is badly compatible with the lack of binocular interaction. It is unlikely that the two visual paths are activated in a statistically independent way by one and the same general arousing mechanism.

For the present the conclusion is, that there is evidence for no or

little binocular interaction in Troxler's effect. Spontaneous fadings of contours occur independently in the eyes. There is no necessity to think of a more central localization of Troxler's effect than the receptive fields of the retina.

§ 6. Combination of spurious and interactive rivalry

In the case of two non-fusing images in the two eyes, the image from one eye may fade by Troxler's effect, while the half-image from the corresponding area of the other eye is still present. Phenomenally this does not differ from the real rivalry situation in which mutual suppression takes place. In both cases only one of the images is present. The signalled confusion of ideas in literature is understandable therefore, but now the question arises as to whether the concept of interactive rivalry is superfluous. This however is not the case for it is known that a foveal patch almost never fades spontaneously. By way of adroit contour stimulation of the other eye, however, it can easily be made to disappear.

The conclusion is, that in most rivalry situations, spurious and real rivalry exist in a mixed form. But because of the phenomenal similarity of these effects it is hardly possible to construct a clear situation in which both types of rivalry can be controlled independently.

Spurious rivalry might be controlled by varying the eccentricity of the stimuli. But rivalry experiments in peripheral view are always subject to considerable 'noise'. Because of the lack of visual acuity and colour sensitivity it is always difficult to decide which of two images is present.

There is however one way to produce a situation in which both spontaneous fading and binocular interaction can be demonstrated: by means of the technique of stabilized retinal images. This technique is independently developed by Ditchburn and Ginsborg (1952) and Ratliff (1952). It consists of an optical system such that the image of a target remains on the same part of the retina, whatever the size of the eye movements made. For details of this technique, reference is made to these initial studies. The most impressive result, in applying this technique, is that a foveally or extrafoveally presented stimulus is not perceptible for more than a few seconds. At first the contours fade, and the target is 'filled-in' by colour and brightness of the surrounding field. After that, colour and brightness impressions slowly decline. Finally, this leads to complete darkness.

It was Clarke (1960) who pointed out for the first time that this

phenomenon is due to the same mechanism as Troxler's effect and this view has become universally accepted. In view of the great similarity in circumstances, and in the phenomena observed there seems to be no reason for doubt. The important difference is, that fading-out can occur foveally with this technique.

Binocular interaction in the fading of stabilized images is, as might be expected from what is known about Troxler's effect, small or non-existent if stabilization is sufficiently controlled[1]. Krauskopf and Riggs (1959) did find a very small interocular transfer in the fading of stabilized images. They measured the total time of visibility of a small black bar in one eye during a 30 sec observation period. When the other eye had been preadapted to a similar bar on the corresponding place, the visibility period was 5-10% shorter than when preadaptation had been on a non-corresponding place.

Ditchburn and Pritchard (1960) provide us with the situation in which real and spurious rivalry occur together. They presented both eyes with a stabilized black Maltese cross of about 25° diameter. These crosses were binocularly concentric, and centred foveally. However, one was rotated 45° with respect to the other. This situation fulfills, apart from the possibility of spontaneous fading, the condition for binocular inhibition: i.e. non-fusing contours were presented on corresponding areas of the retinas. Hence, real binocular interaction may be expected in this situation, but not complete alternation (i.e. exact coincidence of the period of presence of one cross with the period of absence of the other one). The observer reacted by using two keys, in order to indicate whether he saw the left cross, the right cross or (parts of) both crosses.

Our expectations are borne out by the results: neither complete alternation, nor complete independence were found in this situation. The independent spontaneous fading produced periods in which both crosses disappeared. At moments that both crosses were visible, some alternation was produced. When the cross presented to the left eye

[1] The elimination of the effects of eye movements is probably insufficient to produce full stabilization of the image. Accomodation may produce small alterations in positioning of the image. Presumably this is the reason for the periodic reappearance of the image which occurs with the usual techniques of stabilization. Spontaneous recovery, as assumed by Fiorentini and Ercoles (1963), is another possibility, but presumably paralysation of the lens may led to permanent disappearance of the image, as is shown by experiments of Gerrits (1964). Furthermore, as long as simultaneous change in lens contraction in the two eyes is not controlled, some binocular interaction can be expected.

was not perceived the probability that the target for the right eye was also not perceived is substantially less than it was when the target presented to the left eye is perceived.

Troxler's effect makes it understandable why, sometimes in binocular rivalry experiments, and especially using the peripheral field of vision, the entire pattern in one eye appears or disappears at a time. Eye movements produce displacements of the whole pattern accross the retina. Hence, Troxler's effect tends to affect the whole retina at once. A faded target reappears in all its parts after a sufficiently large eye movement. It is not improbable, however, that interactive rivalry is sensitive to eye movements as well. This has been denied by Peckham (1936), but recent experiments by Kaufman (1963) demonstrate the importance of eye movements in binocular rivalry.

CHAPTER III

BINOCULAR BRIGHTNESS AVERAGING

§ 1. Introduction

The intention of this and the next chapter is to discuss two basic mechanisms of binocular interaction. In Chapter V it is explained then, in terms of the interaction of these mechanisms, why a perceptual conflict should arise, if the eyes are presented with non-corresponding contours as in Fig. 1.

The first putative mechanism we call 'binocular brightness averaging'. This term denotes the function of the mechanism responsible for the brightness impression, which arises from equal as well as unequal stimulation of corresponding regions of the retinas. The second mechanism controls the rôle of a monocularly given contour in binocular vision; this is the subject of Chapter IV. The present chapter deals with binocular brightness averaging.

§ 2. Literature

The literature concerning binocular brightness interaction can be devided in three main types. Studies of the first type are concerned with the question whether the eyes can be conceived of as independent detection systems, or whether detection is more or less correlated for the eyes.

In studies of the second type binocular interaction is investigated as to whether thresholds in one eye are dependent upon stimulation of the other eye on a corresponding place.

The third type of study deals with the apparent binocular brightness, when left and right eye are exposed to different luminances.

In the first type of study (Graham 1930, 1931; Crawford 1940; Pirenne 1943; Wolf and Ziegler 1955) binocular interaction generally appears to be slight or non-existent. The slight lowering of threshold in the binocular as compared to the monocular condition can be attributed to statistical interaction of independent processes. When the chance of

seeing a test spot is p for each eye, the chance of not seeing it is $1-p$. But the chance of not seeing it with both eyes is $(1-p)^2$, if the eyes function independently. This is equivalent to a lowering of threshold for binocular vision as long as $p \neq 1$ or 0. This also applies to difference thresholds. We mention one experiment, because of its resemblance to those on Troxler's effect. Dawson (1913) had his subjects observe a ring (about 2° diameter) which was slightly darker than its background. With central fixation, they had to push a key whenever they could discriminate the ring from its background. The observation time was 75 sec. The viewing was alternately binocular and monocular. In the monocular condition one eye was presented with a totally blank, but illuminated field.

Because Dawson gave his results as ratios of positive and negative period lengths, we were able to calculate for each subject and condition the probability of not seeing the ring, $p(N)$. The mean probability for the monocular case was $\bar{p}_m(N) = 0.671$. Under the hypothesis of binocular independence, we expect $p_b(N)$, the binocular non-viewing probability to be the square of the monocular one. Calculation gave $\overline{p^2_m}(N) = 0.429$, while $\bar{p}_b(N) = 0.479$. The difference corresponds statistically to a t-value of 1.37, which is not significant. However, the difference $\bar{p}_m(N) - \bar{p}_b(N)$ reaches a t-value of 8.24 which is significant on the 0.0005-level. Hence, Dawson's data also suggest independency of the monocular detection mechanisms.

In the second type of study (Crawford 1940; Galifret 1954) also little binocular interaction is found. This is further specified by Bouman (1955). He showed that absolute and increment thresholds for vision in one eye are independent of contralateral stimulation, as long as one measures only in periods of dominance of the eye under concern. Furthermore he could show that there is a large increase of threshold for one eye within a short time (about 0.4 sec) around the onset of stimulation at the other eye.

This large measure of binocular independence is not observed in the third type of studies, on apparent binocular brightness. This kind of brightness interaction (with the stimuli in the two eyes differing only in luminance) was studied rather extensively in the last century by Panum (1858), Fechner (1861), Hering (1864), Aubert (1865) and others. In this century only Sherrington (1908), De Silva and Bartley (1930) and Fry and Bartley (1933) reported systematic measurements.

Other studies are restricted to mere demonstration of brightness averaging (Hering 1920, Treisman 1962) or of brightness summation (Ivanoff 1947).

Two at first sight contradictory phenomena of brightness interaction emerge from these studies, in which the eyes are presented with different luminances. Firstly, we have the so-called 'Fechner's paradox', already mentioned in Chapter I. An object is seen binocularly, but with a neutral filter for one of the eyes. When this eye is closed the brightness of the object apparently increases, although the total amount of stimulation decreases. The second phenomenon may be called 'brightness averaging': unequal stimulation of the eyes produces a binocular brightness, which is intermediate between the monocular impressions. Or, put more exactly: intermediate between the impressions obtained if both eyes look at the left eye target alone, or at the right eye target alone. The increase of luminance in one eye raises the binocular brightness impression. The present chapter deals with brightness averaging.

The most extensive measurements on brightness averaging are those reported by Aubert (*loc.cit.*). He kept the right eye field at a constant value, and measured the binocular impression by means of an adjustable comparison stimulus, for different values of the left eye field luminance. In short, in a large range he reports adjustments of the comparison stimulus to a luminance of conditions close to the arithmetical mean of the left and right field luminances. However his procedure may be criticized, since he compared binocular stimuli with a monocular comparison field. It would be better if a binocular test stimulus were compared with a binocular comparison stimulus. A comparison of a binocular and a monocular impression is rather indefinite as we shall see. Sherrington (*loc. cit.*) adopted this paradigm, but he measured the binocular brightness of only five stimulus pairs. His results are not essentially different from Aubert's. He also kept the test field for one eye constant, and varied the luminance for the other eye. It is the only procedure, ever used. The consequence is that nothing is known about the equibrightness function, i.e. different pairs of left and right luminances which are perceived as equal to a comparison field with equal and constant luminance for both eyes. This also holds for the studies of De Silva and Bartley (*loc. cit.*) and of Fry and Bartley (*loc. cit.*). The authors of the first paper kept the right field constant and measured using one of seven luminance values for the left test field. These values covered only a small range: the maximal retinal

illumination was 9.78 trol. Moreover their comparison field was usually separated from the simultaneously presented test field by a large angle. This introduces extra variability in the matching behaviour. They were not able to reproduce Sherrington's findings, at least not in the region where the difference in luminance of the two fields was rather small. The second study (Fry and Bartley) is less open to criticism. Here the left field luminance was varied while the right field luminance was kept constant at 1 cd/ft.^{2} The observer adjusted the comparison field. A large part of the curves is quite linear, but its slope is not as expected from averaging. At this point a question arises as to the apparatus used: where left and right luminances are equal (both 1 cd/ft.^{2}) the observers adjust the comparison field to about 0.85 cd/ft.^{2} In both studies no artificial pupils were used.

De Silva and Bartley demonstrated that in order for an object seen monocularly to appear just as bright as an object seen binocularly it must be 1.27 to 1.44 times as bright, depending upon the experimental conditions. This conclusion is also reached by Fry and Bartley. Binocular vision gives an increase in brightness over monocular vision. This is the major conclusion made from these studies. Therefore the authors use the term 'brightness summation'. They assume that the pathways from each pair of corresponding points in the two retinas converge upon a common pathway in the brain, and this would be the reason that the normal process is not averaging but summation.

In our opinion the size of this summation effect is overestimated, and too much is concluded from it in the construction of a theory of binocular vision. Firstly, other authors have not found such high values for this effect (neither Fechner, nor Aubert, nor Sherrington, nor Ivanoff), and it is much less when the monocular and binocular fields are presented not simultaneously but successively, as Ivanoff (*loc. cit.*) rightly remarks. Secondly, the authors did not control pupil diameter in their experiments (no artificial pupils were used). And thirdly, matching monocular and binocular stimuli is an unstable affair. In the next chapter we return to this situation, and to some factors playing a rôle in it. Nevertheless, this effect is the main evidence for assuming binocular brightness *summation* as the normal process in binocular vision.

Obviously, this cannot be the whole story. Fechner's paradox demands another mechanism, one of binocular brightness subtraction. According to Fry and Bartley, the border contrast of the stimulus in one eye produces a depression of the physiological process in the other eye.

If this depressing stimulus is of low luminance, this luminance does not add enough to the binocular brightness impression to compensate for the depressive effect of the stimulus borders. This is Fechner's paradox. In normal binocular vision summative and inhibitory mechanisms always operate together, but as the authors state, not enough is known to predict the perceived brightness.

This, however, is the main objection to their theory: it remains qualitative. For each binocular brightness phenomenon (including Fechner's paradox, normal binocular vision, and vision with one eye closed) new assumptions have to be made as to the relative power of the two mechanisms, border suppression and binocular summation. It is clear, that while an explanation of this kind is always possible, it is not very useful.

§ 3. Equibrightness curves

In a later stage of our argument we shall need to examine equibrightness curves, i.e. different luminance pairs, producing the same binocular brightness. A fruitful extension of the knowledge of brightness averaging will be obtained by measurements like this, especially when a larger range of luminances is employed and when a different matching technique is used.

Experiment 2

A straightforward way of collecting data for equibrightness curves is to have the observer (*O*) adjust a binocular test field in which the luminance for one eye is fixed by the experimenter and the other one adjustable by *O*, until it produces the same brightness impression as a binocular comparison field with equal luminances for both eyes. A further requirement is that comparison and test field are projected on the same retinal areas, which is the case when both stimuli are centrally fixated.

Apparatus

The apparatus is schematically represented in Fig. 6. The light sources for the test field are two 150 watt Prado projectors P_l and P_r, the current supply of which can be regulated by two Variacs R_l and R_r. Light is thrown on the diffusing screens DS_l and DS_r before which masks can be mounted with holes of the proper size. The projector P_b is used for the comparison field where equal luminance for both screens is needed. This is achieved by splitting the light beam from P_b by a prism and two surface mirrors. Alternation of test field and comparison field is regulated by a mechanism A, so that if the shutters S_r and S_l are closed, S_b is synchronously opened, and vice versa.

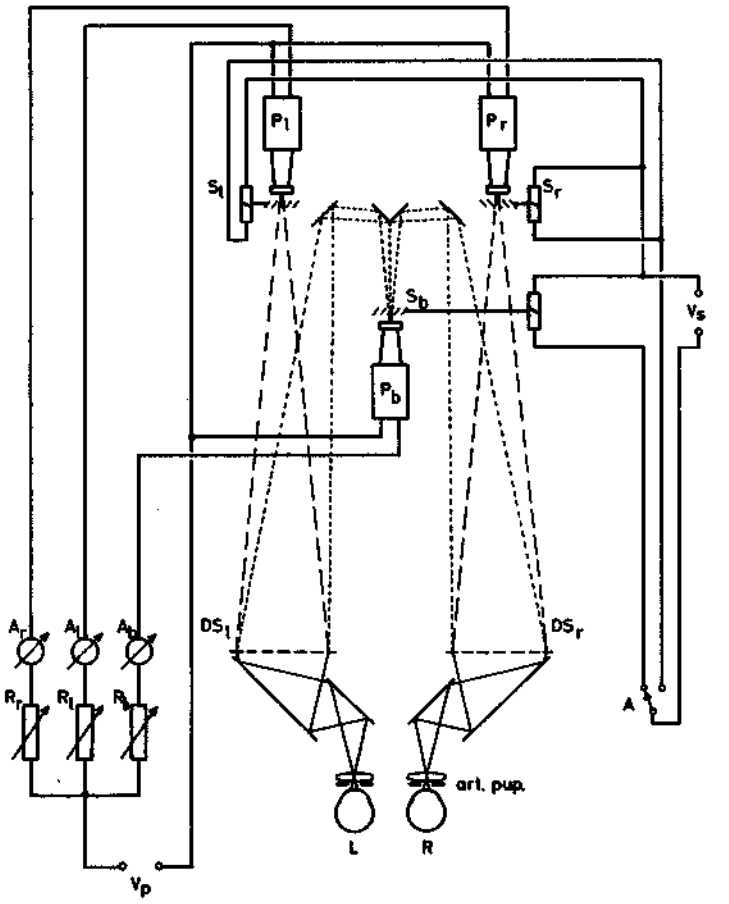


Fig. 6. Diagram of the apparatus. Explanation in text.

The images on DS_l and DS_r are projected to the eyes by means of two surface mirrors and two prisms. A fixation point can be introduced via these prisms. Lenses before the eyes serve to produce accomodation at infinity. Artificial pupils of 1 mm diameter are used. O's head is supported by a chin rest.

Supply voltage has been stabilized. Luminances have been carefully calibrated through the oculars. Luminances which should be equal at successive adjustments are not different by more than 5%.

Procedure. Throughout this and the next chapter the term 'test fields' is used to represent the two monocular fields, mostly unequal

in brightness, representing the relevant stimuli. 'Comparison fields' are the two fields which are always equal in brightness. Either test field or comparison field may be adjusted by *O* according to the conditions of the particular experiment.

Fig. 7. Stimuli used to determine equibrightness curves. The discs subtend 3° of visual angle. Because of experiments to be reported in Chap. IV, the left and the right test and comparison fields contained a concentric circle, 2° in diameter, with outline diameter of 3′.

The stimuli which were used in this experiment are given in Fig. 7. They are circular discs subtending a 3° visual angle, against a black background. The luminance of the two discs in the comparison field was set at a certain value by the experimenter. The luminance of the left test field was increased in small steps (to be specified below), starting at zero, and at every step *O* had to adjust the luminance of the right field until the binocular brightness impression was equal to that of the comparison field. The step-wise increase of luminance in the left test field was continued until a match became impossible. A similar series of measurements was then taken with the luminance of the right test field increased in small steps, while *O* adjusted the left one. These series were obtained for two levels of luminance of comparison field.

Results. The results in terms of equibrightness curves, are given in Figs. 8a,b, 9a,b and 10a,b.
These figures give the data for series with linear increase of the test field luminance, in steps of 2 cd/m^2, starting at zero[1].
First, as a check on the matching procedure, one may note that where *O* makes adjustments, such that the luminances for the test fields are equal, their value is in close agreement with that of the comparison

[1] Measurements from a series in wich the luminance of the test field was increased in logarithmic steps are published elsewhere (Levelt 1965).

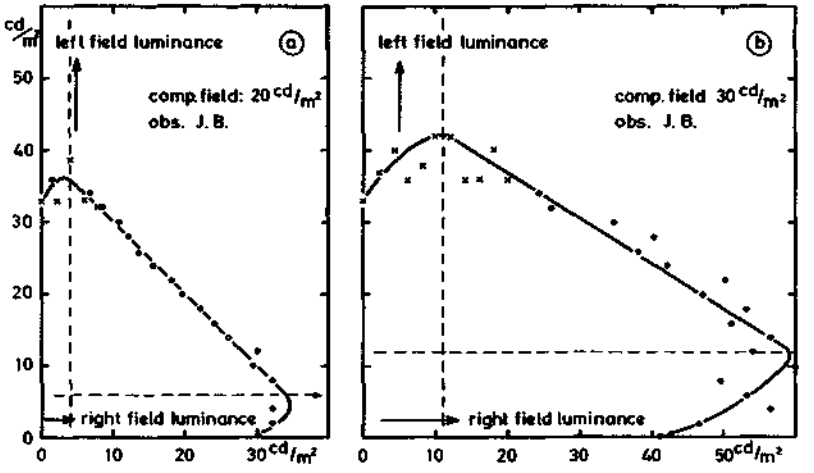


Fig. 8ab. Equibrightness curves (subject J.B.). 20 and 30 cd/m², respectively.
o Observer adjusts the luminance of the right test field.
× Observer adjusts the luminance of the left test field.

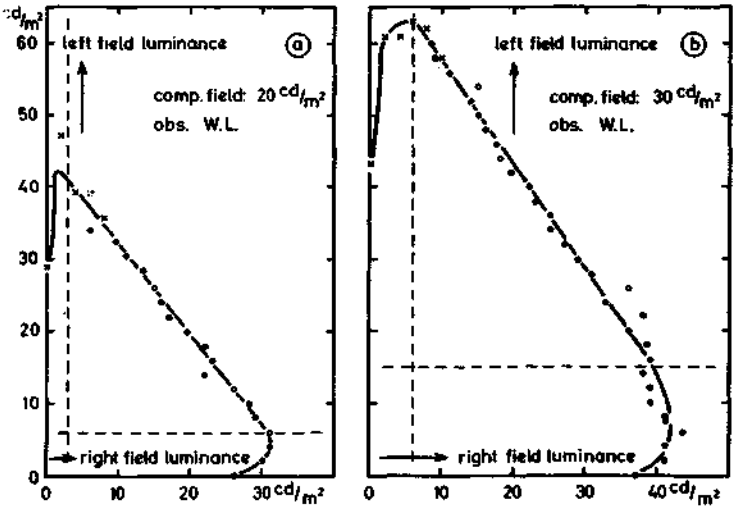


Fig. 9ab. Equibrightness curves (subject W.L.).

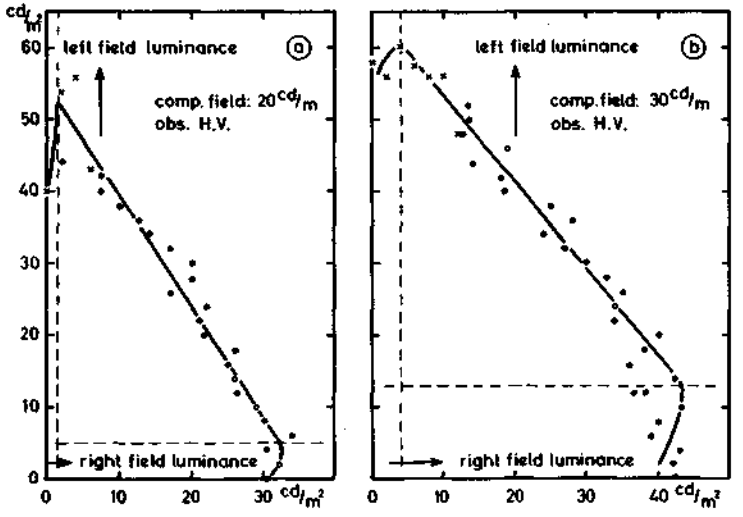


Fig. 10ab. Equibrightness curves (subject H.V.).

field; test field and comparison field are identical in this situation. The general trend of our equibrightness curves appears to be as follows: for test field luminances higher than some value (indicated in the figures by a dotted line) the functions are linear. The slope of the line is different for the three subjects. It is reasonable to suppose that the slope is dependent upon eye dominance; the steep curve in Fig. 9 gives data for an *O* with strong dominance of the right eye. The *O* represented by Fig. 8 does not show such a strong dominance. A difference in sensitivity between the two eyes might be an alternate hypothesis. However, these two subjects have been tested on the Haag-Streit Adaptometer for three minutes after foveal adaptation to 2000 cd/m². This was done for both eyes. Neither of the subjects showed a difference in foveal sensitivity between the eyes during this period. So we maintain the eye dominance hypothesis, although only an exact dominance measurement can be conclusive at this point. However, there exists no unambiguous technique for measuring degrees of dominance.

The linear portions of an equibrightness curve can be expressed as: $w_l E_l + w_r E_r = C$. Here E_l and E_r are luminances (energies) of left and right test field respectively. w_l and w_r can be interpreted as weighting coefficients which account for eye dominance. The fact that the curves are linear (if we disregard their tails) implies that binocular brightness

averaging can be simply described as an averaging of energies, and that thus far there is no reason to claim that brightness averaging is a matter of averaging of 'sensations'. The latter claim was made by Sherrington. Sherrington went as far as to speculate that the sensorium of the right eye is completely separated from that of the left eye. Whatever the truth in this Helmholtzian view, our curves suggest that the binocular brightness impression does not result from simple averaging of monocular sensations. For it is known from psychophysical studies that monocular and normal binocular subjective brightness is a non-linear function of stimulus energy. Irrespective of whether this is a logarithmic function (Fechner), or a power function (Stevens), or any other non-linear function, if sensations were merely averaged, an equibrightness curve could not be a linear relation between monocular energies as in our result. The experimental error in our measurements evidently tolerates slight deviations from linearity, but even a function of power $\frac{1}{2}$ would produce a bend, similar in all curves. Therefore, if binocular brightness is a matter of combining sensations, the results suggest that they would have to be combined in a more complicated manner, in such a way, in fact, that the resulting binocular brightness is the same as if the energies were averaged.

Conclusion. Binocular brightness is constant if a sum of weighted monocular energies is constant; the weighting coefficients are constant for an individual observer. The weighting coefficients change if one of the monocular luminances becomes very low. This non-linear part of the curves will be considered in the next chapter. The difference in weighting coefficients for different observers can be attributed to differences in eye dominance.

CHAPTER IV

MONOCULAR CONTOUR INFORMATION AND BRIGHTNESS AVERAGING

This chapter deals with the second pertinent mechanism in binocular rivalry: the effect of monocular contour information on the binocular brightness impression, and its interaction with the mechanism of brightness averaging.

§ 1. The law of complementary shares

To assess the rôle of monocular contour information, an experiment was performed which is a natural extension of the experiment in the former chapter.

Experiment 3

Procedure. In Exp. 2 equibrightness curves were determined, with the stimuli of Fig. 7, that is with a concentric circle in both the right and the left test and comparison fields. The procedure of the present experiment was the same, except that a circle (again subtending 2°, and concentric with disc circumference) is present in only one of the monocular fields, the other being uniformly illuminated. This applies to both test field and comparison field. The observer was instructed to match the fields for the interior of the circles. The comparison field was kept at 30 cd/m².

Results. Figs. 11a, 12a, and 13a show results for circles in the left field, Figs. 11b, 12b, and 13b for circles in the right field.
The curves are linear again, except for the tails. The linear part of each of these curves may again be described by $w_l E_l + w_r E_r = C$. Firstly, it may be noted that the apparent brightness is per definition the same for the three situations (circle in both fields, circle left or circle right), because the same comparison field luminance has been used[1]. We find for all observers that the three curves coincide in the

[1] Although the comparison fields in the two experiments were equal in luminance, they differed in that in the present experiment a circle was only present

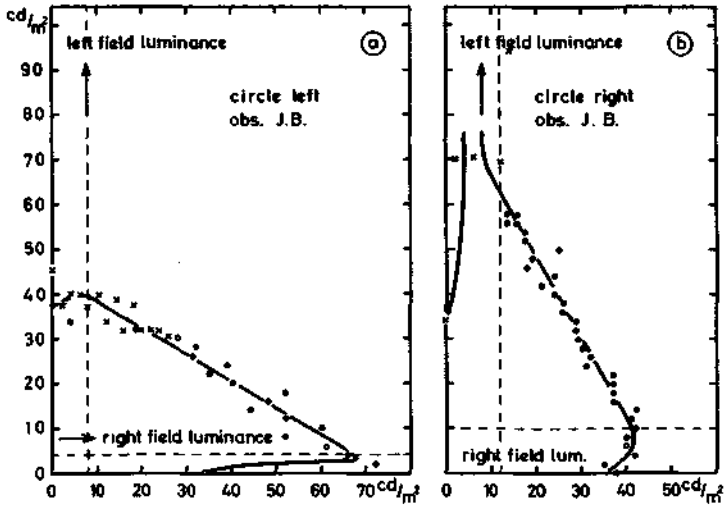


Fig. 11 a-b. Equibrightness curves with monocular contour information (subject J.B.). Circles in left and right test field, respectively. Comparison field luminance 30 cd/m².

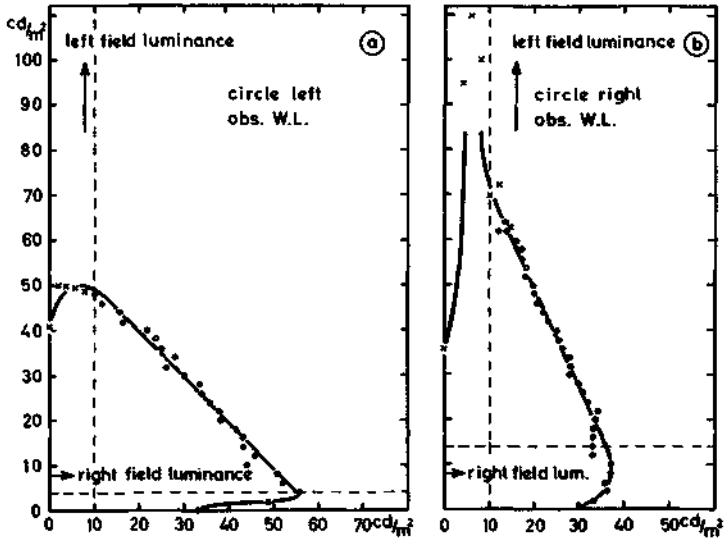


Fig. 12ab. Equibrightness curves with monocular contour information (subject W.L.).

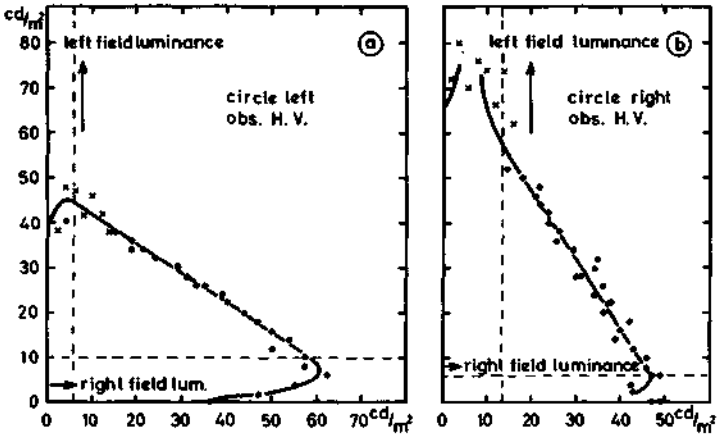


Fig. 13ab. Equibrightness curves with monocular countour information (subject H.V.).

point $E_l = E_r = E$. As the brightness impression is equal for these three situations, we have $(w_{l,1} + w_{r,1})\,E = (w_{l,2} + w_{r,2})\,E = (w_{l,3} + w_{r,3})\,E$. Stated otherwise: the sum of the weighting coefficients is the same for these points, and hence is a constant for the three curves.

Secondly, the important difference between the curves from the same observer is their inclination. Thus the ratio of the weighting coefficients is different when a circle is presented in the left field, in both fields or in the right field.

The combination of these two facts: constant sum and variable ratio of the weighting coefficients may be called *the law of complementary shares*. The law states simply that if the weighting coefficient for the

in one of the fields. One may raise the question whether the elimination of a circle from one of the fields, without changing luminances, affects the apparent binocular brightness of the field. This seems very improbable. All the same, the assumption was checked by having an observer compare a pair of fields of luminance 30 cd/m² both containing a 2° circle to an adjustable field with a circle in the left field only. Ten adjustments were made (Obs. W.L.); their mean value was 30.6 cd/m², the standard error of this mean was 0.49. The assumption may therefore be maintained.

field in one eye is increased, the weighting coefficient for the corresponding field in the second eye is decreased in the same measure. It may be thought of as a specification of Hering's suggestion (see Chapter I).

As may be seen from the curves, the shift in weighting coefficients is induced by the mere presence of a contour. If a circle is presented to the left field only, w_l is increased at the expense of w_r and *vice versa* for the situation in which a circle is given in the right field only.

It is convenient to define a share as a proportional contribution, i.e. with values between 0 and 1. We know that the sum of w_l and w_r is constant. This constant is indefinite, therefore we may set $w_l + w_r = 1$, without loss of generality; w_l and w_r are proportional shares then. Thus, under this particular definition of 'share', the law of complementary shares is expressed as $w_l + w_r = 1$.

In the absence of eye dominance and with a circle in both fields we have $w_l = w_r = \frac{1}{2}$, then. Introduction of a circle in the left field only, gives $w_l > \frac{1}{2}$, and similarly for a circle in the right field.

In conclusion: 1. w_l and w_r are complementary. Their relative magnitude depends on the contour information in the monocular fields. This has been called the law of complementary shares. If shares are defined as proportional contributions, the law states $w_l + w_r = 1$.

2. The description in terms of weighting coefficients was introduced in the former chapter, because of the linearity of the curves. The weighting coefficients were constant for the curve then. This appeared to be the case again for the curves of this chapter. We now find that these weighting coefficients only vary with contour information. The fact that the weighting coefficients are constant as long as the contour information is constant, may be called *the constancy rule.*

These conclusions are answers to the questions put forward in Chapter I, § 4 in connection with Hering's theory. A share of a retina is most conveniently thought of as a share of its illumination. A share is constant as long as contour information is constant.

The law of complementary shares, the constancy rule and the definition of shares as proportional contributions provide us with an easy means to determine what an observer sees, if we know that his shares are w_l and w_r and that the respective luminances of the two fields are E_r and E_l. His brightness impression is namely the same, as when he looks with both eyes at a field with luminance $E_b = w_l E_l + w_r E_r$. For, the such defined pair of monocular fields

(E_b, E_b) is on the same equibrightness curve as the pair (E_l, E_r), because $w_l E_b + w_r E_b = (w_l + w_r) E_b = (w_l + w_r)(w_l E_l + w_r E_r) = = w_l E_l + w_r E_r$.
In the following we shall speak of the apparent brightness produced by some stimulus pair (E_l, E_r) in terms of E_b. E_b is not the psychological quantity of apparent brightness then, but it is the luminance of a field observed with both eyes, which produces the same apparent brightness as (E_l, E_r). We know that the apparent brightness is a monotonic increasing function of E_b, but the character of this function is unimportant for our further discussion.

Weighting coefficients are not constant for the tails of the curves. Can this 'violation' of the constancy rule also be explained by changes in contour information, as was the case in Exp. 3?
It is clear that if the luminance of one test field, say the left one, is below threshold, contour information is present in the right field only. Therefore, for these low values of E_l, w_r will increase at the expense of w_l. So a change of slope of the curve at the tails can be expected on the basis of the contour mechanism. But we are not able to predict the precise function of this non-linear part of the curve; in particular the luminance values at which the weighting coefficients start changing are difficult to estimate. Most likely, this is not at the threshold value for one eye but at some value where the contour has faded out sufficiently. More measurements on this are given by Levelt (1965). The relation of fading out of contours and binocular alternation is further studied in Chapter V.

§ 2. Change in weighting as dependent upon distance from contour

A monocular contour increases the weighting coefficient for the luminance in this eye. The question which will now concern us is whether this effect of a contour is local or general, i.e., is there increase of w for the whole monocular visual field, or is the increase limited to a region in the immediate environment of the contour?

Experiment 4

Procedure and stimuli. The stimuli for this experiment are given in Fig. 14. They are four pairs of patterns, subtending 5°, with circles drawn within them as indicated. These stimuli were used for both the test and comparison fields. The difference again is that in the test

field luminances are unequal: 250 cd/m² for the left eye and 25 cd/m² for the right eye, whereas in the comparison field they are equal. In this experiment the observer had to adjust the comparison field, until the brightness in the centre of the upper circle looked equal for

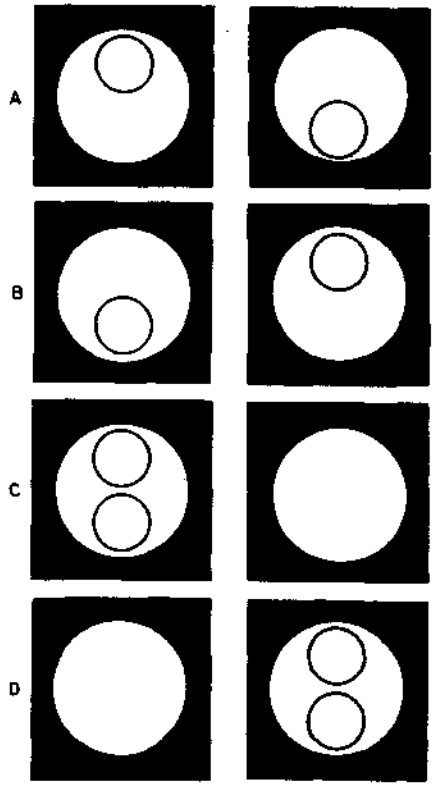


Fig. 14. Four stimulus pairs used to test local vs. general influence of contours.

both test and comparison fields. Four observers served in this experiment. The four different stimulus conditions were given to them in an order which was varied according to a latin square design. 1 mm-artificial pupils were used.

Results.

Table 1 gives the results in terms of the adjusted luminance in the comparison field. An analysis of variance reveals significant differ-

TABLE 1. Comparison field adjustments in cd/m² of four *Os*. (Exp. 4)

Condition	A	B	C	D
Observer				
1	202	53	195	70
2	180	43	190	50
3	180	57	223	80
4	202	117	270	104
Mean	191	67.5	219.5	76

ences between the conditions. First, the C-pair results in a higher value than the D-pair ($p < 0.001$). Since for the C-pair the contour is in the more luminous left test field, whereas for the D-pair it is in the less luminous right field, this result is another confirmation of our thesis, that contour information has an influence upon the weighting coefficient. Secondly, in both pairs A and B one circle is present in the more luminous left field, and one circle in the dimmer right field. If the influence of the contour extends to the whole field, the matching for the upper circle area in A and B should not be different. If however only the direct environment of the contour is effective, the comparison field for A should be adjusted to a higher luminance than that for B. Table 1 shows that the latter is the case (the difference is significant at 0.005-level), whereas the difference between A and C does not reach significance, nor that between B and D. The conclusion is therefore, that the weighting coefficient is increased only for the immediate neighbourhood of contours, and not for the visual field as a whole.

§ 3. Amplitude of the weighting variation

The next question follows immediately: to what value does w increase at the fixation point if the distance between the fixation point and the contour is made smaller and smaller? In other words, this question refers to the maximal amplitude of the w for an eye (and thus for the minimal w for the contralateral eye).

Experiment 5

Procedure. The stimulus conditions for this experiment are shown in Fig. 15.

The right test field is a square of 14° × 14°. Its luminance is fixed at 100 cd/m². The right comparison field is identical, but its luminance is adjustable by the observer. The left test field consists of two parts: a central disc of variable size, with luminance fixed at 12 cd/m², and

a surrounding field ($14° \times 14°$) at luminance 3.7 cd/m². The left comparison field has the same pattern; the luminance of the central disc is always the same as that adjusted by the observer for the right field, the luminance of the surrounding area is always 1/3.25 of that of the central disc. The observer had to adjust the comparison field until the brightness of the central disc appeared equal for both test field and comparison field. The observer was requested to fixate the centre of the disc.

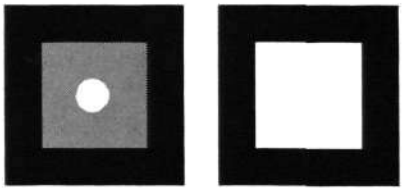


Fig. 15. Stimuli used to determine w_l as a function of field size.

In this experiment boundaries between two different luminances were used instead of contours on a uniform background as in the former experiments. The reason for this is, that it is impossible to make a trustworthy brightness match of the area within a contour of 1° on a relatively large uniformly illuminated background, with the instruction to neglect the brightness of the surrounding field. The problems as to brightness contrast that might arise with this stimulus arrangement have been minimized in two ways. The central disc is brighter than the surrounding area, whereas the brightness contrast effect is only substantial in the other direction, i.e. when a stimulus is given against a more luminous background. Moreover the ratio between disc and surrounding luminance is equal for test and comparison field, and constant throughout the experiment.
The size of the disc was varied; the four values are 7°, 5°, 3° and 1° of visual angle. The conditions were presented in an order according to a latin square design. Two groups of four observers took part in the experiment.

Results.
Individual values of w_l have been calculated for the four disc sizes. The results are given in Table 2. An analysis of variance shows that w_l increases with decreasing diameter of the discs (the regression is

TABLE 2. w_l-values of eight *Os* at different disc sizes (Exp. 5)

Size	1°	3°	5°	7°
Observer				
1	.835	.786	.741	.798
2	.956	.873	.941	.875
3	.997	.981	.974	.968
4	.911	.830	.765	.792
5	.939	.914	.824	.801
6	.990	.900	.881	.864
7	.824	.810	.790	.773
8	1.002	.998	.941	.937
Mean	.932	.887	.857	.851

significant at the 0.001-level). In Table 2 it is seen that at 1° for the observers 3, 6, and 8, w_l approaches the unit value as closely as adjustment errors permit. In view, moreover of the increasing trend in the mean w-values with decreasing size of the disc, the data strongly suggest that in the immediate neighbourhood of a monocularly presented contour, binocular brightness impression is exclusively determined by the luminance of this monocular field. The strongly localized contour effects in the former experiment (Table 1), compared with the relatively high w-values for all sizes in Table 2, suggest that the extent of the w-variation is limited by the presence of a contour in the other eye. Furthermore, a boundary may be more effective than a contour.

§ 4. Fechner's paradox

Fechner's paradox can now be understood as follows. If a neutral filter is placed before the right eye, $E_b = w_l E + w_r t E = E(w_l + w_r t)$, where t is the transmission of the filter. If the right eye is closed, w_l equals unity, so that $E'_b = E$. Since $w_l + w_r = 1$, and $t < 1$, it follows that $w_l + w_r t < 1$, and hence $E'_b > E_b$. The apparent brightness increases if the right eye is closed.

This argument implies however, that the law $w_l + w_r = 1$ remains valid for monocular observation. There is some evidence that this is not true without qualification. In fact, one may interpret our data for $E_r = 0$ and for $E_l = 0$ (see Figs 8 to 13, especially the results of H.V.), as an indication that $w_l + w_r < 1$ here, since $E'_b < E_l$ and E_r

respectively. In Chapter III this appeared to be the main point in the studies of Fry, De Silva and Bartley (*loc. cit.*). In our terminology, they concluded from it, that $w_l = 1$ and $w_r = 1$, a mere summation of the stimulus effects in normal binocular vision. However, to make it acceptable that the law of complementary shares holds even in the case of monocular vision, two considerations have to be taken into account.

1. Matching a monocular and a binocular brightness appears to be a rather unstable affair. Day-to-day variability is high. Observers have a feeling that at every new experimental session some arbitrary criterion is chosen. This feeling of uncertainty is absent for binocular-binocular matchings.

2. To check whether the assumption that $w_l + w_r = 1$ remains valid for monocular observation, one is bound to make use of a very small test field (or comparison field) to ensure that this field as a whole is sufficiently close to contour information for its weighting coefficient to approach unity. Closeness to contour information may be a point, for in Fechner's original experiments (1861) the paradox was not producible for filter transmission closely approaching unity (*loc. cit.* p. 420). This indicates that $E'_b < E$ in the above sense. This is necessarily the case when $w_l < 1$, because $E'_b = w_l E + (1 - w_l).\ 0 < E$, then. According to Table 2 $w < 1$ at greater distance from the contour, and this is precisely Fechner's situation, because he instructed his subjects to look at the blue sky through the filter.

For these reasons it does not seem necessary to reject the law of complementary shares for the case of monocular stimulation. And apart from that, our explanation of Fechner's paradox would not be invalidated if the law of complementary shares has to be qualified for the monocular viewing condition. A suitable choice for the transmission of the filter should always compensate for minor deviations from the law.

§ 5. Schematic diagram of the mechanism

The general conclusion of the experiments reported so far in this chapter may be summarized with the help of the diagram given in Fig. 16.

This figure displays both the averaging and the contour mechanism. It is intended simply as a mnemonic device and has no further pretensions. It is drawn as an electric flow-diagram.

Luminances E_l and E_r are presented to the eyes; these may be thought

of as voltages in the electrical metaphor. They are weighted by the balance B. Their weighted sum E_b is the basis for the binocular brightness impression. If B is seen as a potentiometer in electrical terms, w_l and w_r are variable resistances with a constant sum representing the law of complementary shares. As a result, the tension in the channel past B is $E_b = w_l E_l + w_r E_r$.

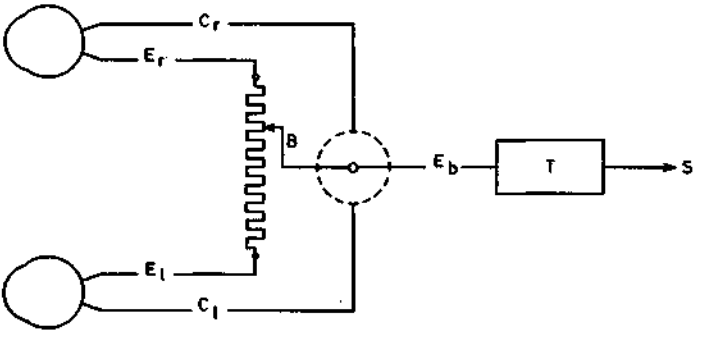


Fig. 16. Schematic representation of the interaction of monocular contours and luminances in binocular brightness averaging.

The weighting coefficients depend upon contour information, as indicated by the channels c_l and c_r to B (These determine the position of the potentiometer). If contour information is similar for both eyes the weighting coefficients are determined by eye dominance only. In the absence of eye dominance they are equal to $\frac{1}{2}$. If contour information is present for one eye only, the weighting coefficient for this eye increases (to a maximum of unity), with a similar decrease for the coefficient of the other eye, according to the law of complementary shares. The whole system applies to a small area of the visual field only; for a different area a similar mechanism must be postulated in which parameters may be different. Some hypotheses as to the minimum area for which the constancy rule for the weighting coefficients is valid, will be given in Chapter V.

If one can maintain that the binocular brightness impression is a function of averaged energies, the 'translation' T of the weighted energies into a binocular brightness sensation has been simply located in the diagram beyond the averaging process (T can be imagined as a device with some non-linear amplitude transfer characteristic). In every point of the visual field, the apparent brightness is thus determin-

ed by the left and right eye luminances in that point and by left and right eye contours near the point.
The remaining part of this chapter is devoted to the testing of a number of predictions derived from this mechanism.

§ 6. A brightness paradox

A rather paradoxical stimulus situation can be constructed from the schematic diagram.

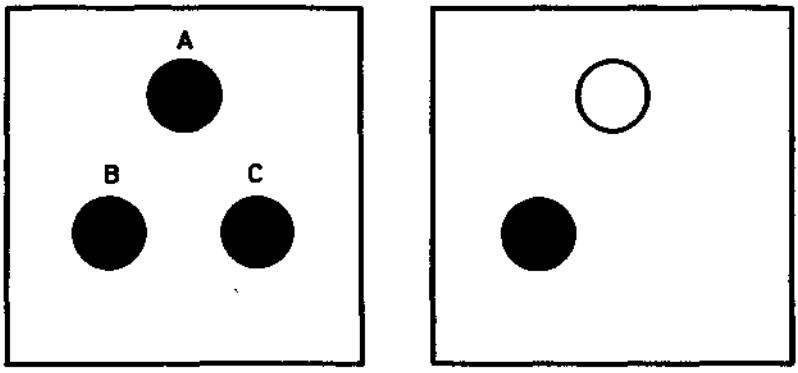


Fig. 17. Stereoscopically the disc A is considerably brighter than C, while B and C are not very different in brightness.

Fig. 17 be presented stereoscopically. Compare discs A and C. For the centre of these discs the stimulations of the eyes are identical, black for the left eye, white for the right eye. Will therefore the apparent brightness of A be equal to the stereoscopic brightness of C? And compare discs B and C. The stimulation is quite different for these discs, both are black in the left eye, but C is white in the right eye, whereas B is black again. Does C in fact look substantially brighter than B does? These questions may be answered by applying the rules diagrammed in Fig. 16. For the sake of simplicity, the luminance of the black discs is supposed to be zero, whereas the bright field has luminance 1.
Disc A: a contour is present in both eyes, therefore – disregarding eye dominance – $E_b = \frac{1}{2}.0 + \frac{1}{2}.1 = \frac{1}{2}$.
Disc B: corresponding contours in both eyes: $E_b = \frac{1}{2}.0 + \frac{1}{2}.0 = 0$.
Disc C: a contour is only present in the left field, hence $w_l \to 1$. For

$w_l = 1$ we get $E_b = 1.0 + 0.1 = 1$, so $E_b \to 1$ in this situation, dependent on the size of the disc.
Hence both questions should be answered negatively. Disc A will look brighter than C, whereas B and C will not differ very much. This was tested by the following experiment, but the reader may verify it himself by using a stereoscope to examine Fig. 17.

Experiment 6

Procedure.

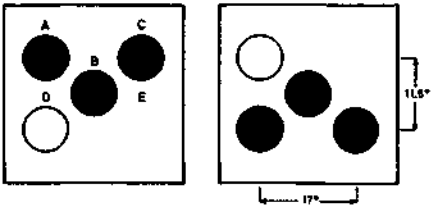


Fig. 18. Stimuli of Exp. 6. Explanation in text.

The stimuli used in this experiment are represented in Fig. 18. They differ from Fig. 17 only in that a disc D is added, which is similar to A but with the binocular interchange of ring and disc. Furthermore a disc E is added, which is a similar transformation of C. The angular distances between the disc centres are stated in the figure.
Two situations were studied: all discs subtended 8° or 3°. In both cases the background luminance was 1000 cd/m²; the discs had a luminance of 110 cd/m². The observer looked through artificial pupils of 1 mm diameter. Five out of ten subjects were first presented with the 8°-situation, followed by the 3°-situation, and the other five subjects were presented with the 3°-situation followed by the 8°-situation. The brightnesses were compared in pairs. The experimenter mentioned one of the ten possible different pairs, and the subject judged which of them was the brighter one; this was repeated for each of the ten different pairs. This is the choice experiment. After this, the experiment was repeated, but now the subject was requested to scale the brightness difference on a seven point scale as indicated in Fig. 19.

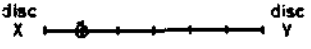


Fig. 19. Method of scaling used in the scaling experiment (score: X = 6, Y = 2).

The meaning of the scoring like the one in Fig. 19 is: disc X is brighter than disc Y; score: X = 6, Y = 2.
This scaling experiment was added since in the choice experiment small differences in brightness are given the same weight as large differences. This may led to overstatement of small differences.
The ten different pairs were judged by the ten subjects in an order corresponding to a latin square design. Before the first stimulus presentation a rough estimate was made of the subject's eye dominance in the following way. The subject fixated the experimenter's right eye (e). The experimenter moved his index finger (i), between subject's nose (n) and e, perpendicular to the axis ne, and parallel to the line connecting the subject's eyes. The subject had to report when i passed in front of e. This was repeated a number of times starting from either side.

Hypothesis. Reasoning as in the comment on Fig. 17 one should expect that discs A and D are brightest. The difference between them depends only upon eye dominance; this is also true for the difference between C and E. These two discs will be nearly as dark as B, which is expected to be the darkest. Because six of the subjects were clearly right dominant, three left dominant and one indefinite, A and D will be the brightest discs in this order of brightness, whereas C, E and B will be the dark discs; they will grow darker in this order, but their mutual difference will be small with respect to their difference from A and D.

Results.
1. Choice experiment. The number of times a definite disc was judged the brighter one of a pair was summed over the ten subjects. The maximum score for a disc is 40, the minimum score 0. In Fig. 20a the results for the 3° and 8° conditions are represented. It was not possible to construct a psychophysical scale from the law of comparative judgement, because many relative frequences were equal to 1 or 0. It is clear from Fig. 20a that the results are in accordance with the prediction.
2. Scaling experiment. The relative unimportance of the differences between C, E, and B and between the two size conditions appears from Fig. 20b, which represents the sum of the scaling-scores for the ten subjects. The maximum score for a particular disc is here 280, and the minimum score 40. As expected, small differences are leveled here, or more precisely, less overestimated.

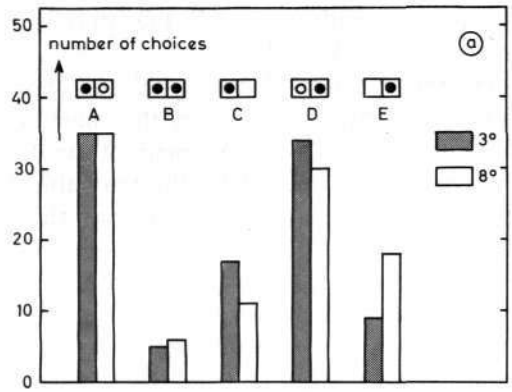


Fig. 20 a. Choice experiment. Number of 'brighter'-judgements for the discs shown in Fig. 18.

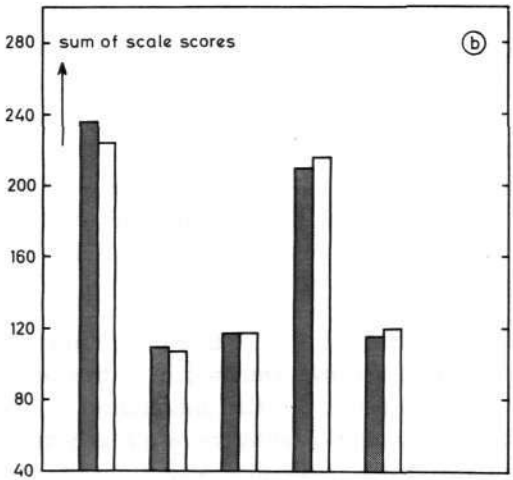


Fig. 20 b. Scaling experiment. Sum of scaling scores for the discs shown in Fig. 18.

The results are in good agreement with the expectations. The largest difference in apparent brightness is between the pair A, D and the triad C, E, B. Size conditions appear to be immaterial in this experiment.

§ 7. An argument against the Gestalt view

On the basis of the considerations in the last section, it is possible to construct a stimulus situation which produces a counterargument against the Gestalt view on binocular rivalry (as formulated by Gellhorn, *loc.cit.*) In Chapter I it was concluded that the only explicit Gestalt rule for the binocular interaction of two Gestalts states that parts of one Gestalt never appear together with another Gestalt from the other eye. Otherwise stated: in binocular rivalry a Gestalt is present or absent in its entirety, it is never deformed.

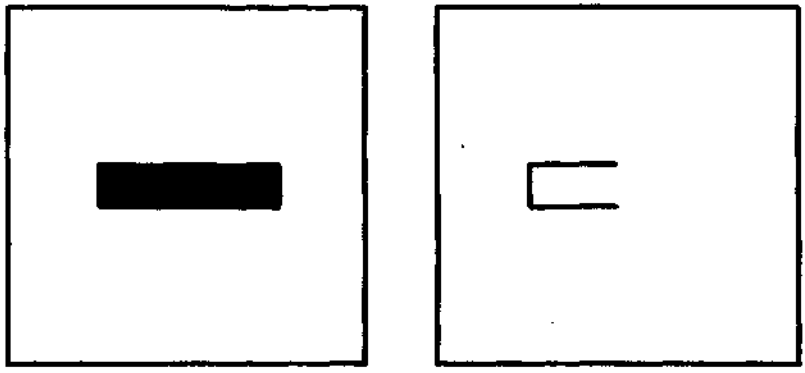


Fig. 21. An argument against the Gestalt view. The Gestalt of the bar is disturbed, stereoscopically. The left half appears grey, shading into black in the right half.

The counter example is given in Fig. 21. The Gestalt rule does not lead to very specific predictions in this situation, but one of three things has to occur.

1. Only the hook is seen, not the bar.
2. The bar is seen, not the hook. From the general Gestalt law of Prägnanz, this is the more likely situation, but probably 1. and 2. will alternate.
3. Both Gestalts are present together. This seems to be the most obvious possibility: the hook may coincide with the contour of the left half of the bar, there is no problem with crossing contours.

What is the expectation from our model? In the left part of the binocular field a contour is present in both eyes. Putting the bar's luminance equal to zero, and the background's equal to unity, we have for the left part of the field $E_\flat = \frac{1}{2}.0 + \frac{1}{2}.1 = \frac{1}{2}$ (grey). In the right

part a contour is only present in the left field, so $w_l \to 1$, therefore $E_b \to 1.0 + 0.1 = 0$ (black). So, the bar will be disturbed in this situation, it will be grey in the left part and passing to black in the right part. Moreover it cannot be a 'background' for the hook as in Gellhorn's reasoning about Fig. 4. The present prediction is more definite than the Gestalt one, and as anyone may verify by means of a stereoscope it is borne out against the three Gestalt possibilities. This type of stimulus can be multiplied at will using the same principles of construction.

Gestalt effects have to be placed at a more central level than the functioning of binocular rivalry. This was Wilde's conclusion (see Chapter II), but his arguments were only valid for what appeared to be spurious rivalry.

§ 8. Colour contours

Until here it was always a luminance gradient which acted as a contour and which induced a particular 'position of the balance'. The luminance distribution perpendicular to the contour direction always was as schematized in Fig. 22a or b. It is an open question whether a colour contour, i.e. a border between two different colours will influence the position of the balance in a similar way as a luminance gradient. Otherwise stated, is a colour gradient coded in the same way as a luminance gradient in this respect?

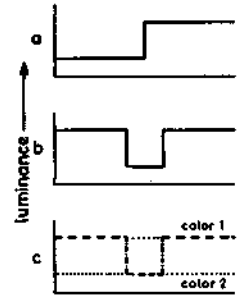


Fig. 22abc. Contours as luminance gradients (a and b), or as colour gradients (c).

Experiment 7

Procedure. To study this question, one has to use a colour gradient, which is not at the same time a luminance gradient,as shown in Fig. 22c. A possible influence of such a gradient on the relative contri-

butions of the eyes to binocular brightness perception can be investigated by the stimuli of Fig. 23. The contour in the left field is a colour gradient as in Fig. 22c: a red circle on a white background without brightness gradient. If this contour raises the weighting coefficient of the left eye, on should expect that the upper disc looks brighter than the lower one.

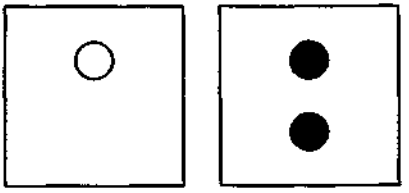


Fig. 23. Stimuli of Exp. 7. Left field: 60 cd/m² red ring with outer diameter of 4.5° and contour diameter of 13.5′; background: 60 cd/m². Right field: 3.5 cd/m² grey discs (diameter 4.5°); background 60 cd/m².

Apparatus. These stimuli were produced by the equipment represented in Fig. 24. The left field was illuminated by the projectors P_1 and P_2. P_1 projected the photopositive of the left field stimulus (see Fig. 23) via the mixing cube MC on the left diffusion screen DS_l. By means of P_2, the photonegative of the same stimulus (white circle on black background) was projected on the same diffusion screen, but via a colour filter CF (Cinémoid filter Rubis 14, $\lambda > 620$ nm). The white photopositive could be made to coincide exactly with the red photonegative by means of fine adjustment screws. This produced a red circle on a white background. The current supply of the projectors could be regulated by

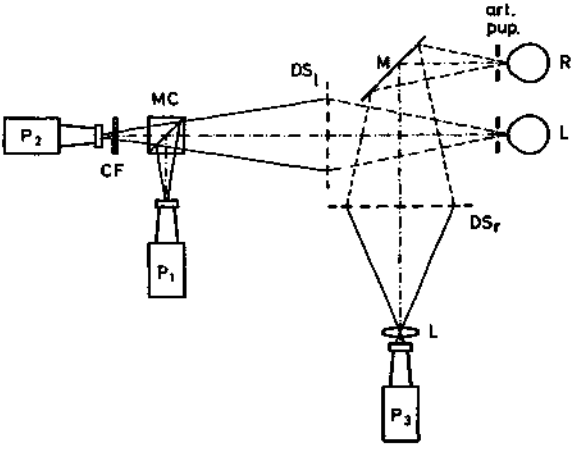


Fig. 24. Equipment for the presentation of the stimuli shown in Fig. 23. Explanation in text.

Variacs. By way of an extra test field in the slides, the luminances of the red and the white part of the stimulus could be equalized. This was done by way of the flicker photometer described by Walraven and Leebeek (1958). This measurement technique was used to account for the differences in sensitivity of the eye for different colours. The luminance of circle and background was 60 cd/m². The right stimulus was produced by projector P_3. Measured via mirror M, the white background of this stimulus was likewise 60 cd/m², whereas the luminance of the discs was 3.5 cd/m². The subject used artificial pupils of 2 mm diameter in this experiment.

In the first phase of the experiment the left field was covered, and the observer was asked whether one of the two discs was brighter than the other one, or whether they were equally bright. The observer alternately fixated the two discs.
After this the left field was added, and adjusted in such a way, that the red ring was concentric with the upper disc. Now the same task was repeated. Ten subjects served in this experiment.

Results. These are represented in Table 3. It is clear from this table that the introduction of the red circle changes the brightness of the upper circle relative to the lower one (this is significant at about 0.01-level). The conclusion from this experiment is that a pure colour gradient affects the position of the balance in a way similar to a luminance gradient, and is therefore 'coded' in the same way in this respect.

TABLE 3. Brightness comparisons of Exp. 7

Observation condition	upper circle looks:		
	brighter	equal	darker
Monocular (right eye)	0	9	1
Binocular	9	1	0

The statistical significance of the result was estimated as follows. Assuming that the perceived brightness in the monocular situation is equal for the two discs, which is reasonable from the physical equality in luminance and statistically 'unprofitable' in view of the first row of the table, this same assumption may be tested for the binocular situation, by calculating $P(1:9)$, that is the chance that at most one observer gives a 'darker'-judgement. (This is again unprofitable, because it was an 'equal'-judgement).

$$P(1:9) = \frac{\binom{10}{9} + \binom{10}{10}}{2^{10}} = 0.0107,$$

hence the assumption can be rejected.

§ 9. Time contours and brightness inertia

The weighting coefficient is not only affected by a static monocular contour, but also by what may be called a time-contour. We mean by this an abrupt change in the stimulus presented to one eye. This leads to a temporary increase of the weighting coefficient for that stimulus, and hence to a decrease of w for the other eye.

The effect of this time-contour was first shown by Bouman (1955). He intermittently presented a bright (red or green) induction field **I** to the left eye. The field subtended 10°, and was centrally fixated. Its on-period was 1.5 sec, followed by 2.5 sec darkness. A 0.03 sec testflash **T**, 5° or 10° in diameter was concentrically presented to the other eye at various stages of the light-dark cycle, in order to determine the right eye's sensitivity at these moments. It was found that the threshold increased for some time around the moments of brightness change in the left eye (on and off). The effect of the increase was faster than that of the decrease. The duration of the rise of threshold was dependent on the stimulus conditions, but 0.1-0.2 sec was quite normal for this period. This can be understood in terms of our balance. At moments of stimulus change the balance will shift to the left eye channel. The weight given to the test stimulus is then correspondingly reduced, and hence the threshold increases.

Similar results come to the fore in later work by Fiorentini and Bittini (1962), in which the evidence from an earlier study of Fiorentini and Radici (1961) is referred to. These authors determined increment thresholds of **T** at different moments around the onset of **I**. **T** and **I** did not occupy corresponding area's of the eyes as in Bouman's experiments, but were adjacent square fields (2.5°) with angular separation of 1°, with fixation in between. The threshold curve obtained parallels Bouman's. Its amplitude is, however, much smaller than in Bouman's results from experiments in which **I** and **T** had corresponding contours. In the other experimental condition of Bouman (**T** 5° and **I** 10°), where contours did not correspond, the amplitude was also much smaller (about five times).

Fiorentini and Bittini were not able to show a rise in contrast sensitivity within **T** at the moment of onset of **I**. They did their experiments by flashing a 30 msec test spot (40′ diameter) in the centre of **T**, together with the onset of **I**. This contrast sensitivity was compared with the one when **I** was not presented. Although the authors could not find an adequate explanation for this constant contrast sensitivity, one of their other experiments may throw light upon this.

They showed that the brightness of **T** was temporarily reduced when **I** was presented. This is another demonstration of the effect of a time-contour upon the weighting coefficients. The w for **I** is temporarily increased, and by the complementary shares mechanism the one for **T** is correspondingly reduced. But, if this reduction extends over **T**, it must also extend over the small testspot of the contrast experiment. In other words: presentation of **I** does not affect the subjective brightness ratio of testspot and **T**, and hence the contrast threshold is not increased in the Weber-Fechner region of luminances.

The experiment in which the temporary brightness reduction of **T** was measured moreover showed another effect, which may be called brightness inertia. The brightness reduction of **T** was clearly retarded with respect to the onset of **I**. The authors measured that the brightness reduction only became apparent after 90, 60 and 140 msec for three observers respectively. This could not only be measured, but it was also phenomenologically apparent. The observers first saw the appearance of **I**, and distinctly after that a temporary decrease in brightness of **T**. In terms of weighting coefficients, the change of w is slow with respect to the transmission of contour information, or in terms of the diagram Fig. 16, the balance exhibits inertia. A stimulus presented to the left eye comes through immediately, as long as the balance is not in its extreme right position. But it takes some time, before the balance is shifted enough to make the reduction of w_r noticeable.

The brightness inertia in the shift of weighting coefficients also predicts what has to be expected if Fig. 1, the orthogonal grids pattern, is presented in a short flash. Anticipating the discussion of alternation in Chapter V, we may observe that, looking at Fig. 1 through a stereoscope, one normally has the impression of an ever changing field of bar segments from both eyes. We may say, that the balance is alternatingly in either of the two extreme positions.Now, if this shifting in weighting coefficients is slow in comparison to the transmission of contour information, the appearance of the patterns should be quite different if presented stroboscopically; it should look like a mesh-work, bars normally crossing each other ($w_l = w_r = \frac{1}{2}$).

We performed this experiment with flashes of 100-200 msec. The expectation was borne out: one clearly perceives a mesh-work in this situation. Its appearance does not differ essentially from a monocular superposition of the two grids.

Another confirmation of this can be found in a recent article by

Kaufman (1963). He simultaneously flashed a horizontal grid in one eye and a vertical one in the other eye in a continuous series of short flashes. Their on-phase lasted 100 msec, against an off-phase of 900 msec. Neither of his four observers reported rivalry in this case, they saw a grid, as in graph paper, or a black field filled in with white squares. All four saw rivalry in the continuous observation period. Kaufman attributes this result to the absence of eye movements in the flash situation. This may be a factor indeed, but it can not be the whole explanation. Ditchburn's results on rivalry with stabilized images (see Chapter II) show that eye movements are not essential to binocular rivalry, and Kaufman is not inclined to place too much weight on his eye-movement hypothesis either. Therefore inertia in the visual process seems to be a possible alternative explanation.

Two summarizing remarks conclude this section.

1. Time contours induce temporary shifts in weighting coefficients, comparable to the shifts induced by a permanent 'spatial' contour.
2. The change in luminance weighting as dependent upon contours is slow as compared to the transmission of contours. One may speak of brightness inertia.

§ 10. Metacontrast

Brightness inertia and dependency of apparent brightness on contours are not specifically binocular phenomena. In monocular vision similar things occur. We mentioned already the case of stabilized images (Chapter II). Brightness appeared to vanish gradually after the disappearance of clear contours. Furthermore, Crawford (1947) studied the effect of time-contours in monocular vision (**I** and **T** in the same eye). The experimental conditions were very similar to Bouman's, except that monocular vision was concerned. His results are also similar to Bouman's. This suggests the existence of a fundamentally similar mechanism in both cases. But the resemblance of monocular and binocular situations may even be so striking, that the binocular rivalry phenomena of § 6 can be imitated in monocular vision.

The monocular contour and inertia phenomena under concern are known as *metacontrast* (Stigler 1910) or generally *visual masking*. In the context of the present study we are not able to go into the extensive literature on this field (for a general review see Alpern 1952) but present a summary of the data bearing on the present section.

Alpern (1953) found that a 5 msec flash of light is appreciably reduced in brightness when it is followed by a second 5 msec flash which

excites an immediately adjacent non-overlapping retinal region. This effect is maximal when the time interval between the onsets is in the range of 100-150 msec depending on some experimental conditions. Werner (1935, 1940) – probably on the basis of original measurements by Wildhagen – and Kolers (1960, 1962) found a similar optimal interval for the metacontrast effect.

The visual angle between first and second stimulus plays a significant role: the metacontrast decreases with an increase in visual angle. (Werner, Alpern, Kolers ibid.).

Dark stimuli on a bright background give a similar effect, e.g. a dark disc is less detectable if it is followed by an enclosing black ring (Werner, Kolers). From these and other experiments it appears that the metacontrast arises in the first place not from masking by a light stimulus, but from the presence of a contour, irrespective of the direction of its gradient (Kolers 1962). A non-contoured light stimulus is rather ineffective. This will be shown in our experiment as well. This fact was not recognized by Alpern (1953). In short: a test flash **T** is inhibited by an induction flash **I** if **I** is contoured and if angular separation is not too large. The inhibition is maximal if **I** is flashed 100-150 msec after the onset of **T**. In genesis, this phenomenon probably resembles the binocular phenomena of the foregoing section, because 1. the weighting of a field **I** in metacontrast, i.e. its inhibiting power, is dependent on the presence of contours, and 2. brightness formation appears to be slow with respect to contour formation: metacontrast is maximal at 100-150 msec after the onset of **T**. This is also valid for dark flashes on bright backgrounds. This cannot be due to a difference in latency times, for such a difference generally does not exceed 30 msec for luminance differences of 2.5 log-units (Alpern 1954).

As a model for metacontrast, a mechanism may be assumed resembling the model of binocular weighting. Supposing that the inertial brightness formation of the first stimulus can be broken off by the contour formation of the induction stimulus, we would have an antagonistic situation similar to the antagonism in binocular weighting. It may even be visualized by a similar functional diagram. The left and right channel of the diagram of Fig. 16 have to be replaced by respectively a **T**-channel and a **I**-channel. Brightness inertia would then again be inertia in the displacement of the balance. For an interstimulus time t of about 30 msec or less, contour and brightness formation simply summate. In terms of the balance, it is too massive to make an ap-

preciable move within this time, and hence transmits both stimuli with about equal strength.

For $30 < t < 150$ msec, the brightness of **T** is in a growing state, when **I** is presented. This brightness formation of **T** is interrupted by the presentation of **I**, whereas **I** can be fully transmitted. This second stimulus is therefore necessarily dominant over the first one. This is in agreement with the data on metacontrast. Progressive masking (paracontrast) is always of minor significance. In balance terms, at the presentation of **T**, the balance starts moving to the T-channel. This movement is interrupted however by the presentation of the contoured **I**. It then reverses and **I** is fully transmitted because no other disruption of movement takes place.

For $t > 150$ msec, the inertia of brightness formation is small with respect to the interstimulus time and both stimuli may pass in succession – the balance attains both extreme positions in succession.

The brightness inertia in metacontrast is of the same order of magnitude as in the binocular interaction situation, about 100 msec. However, the intention of using a similar scheme of description for both effects is not in order to suggest a law of complementary shares for metacontrast, but only to provide an antagonism in the effects of **T** and **I**. A far less stringent rule of interaction may be sufficient. One may for instance think of a storage process, in which the introduction of **I** leads to erasure of **T**. In the words of Averbach and Sperling who described a situation similar to metacontrast (1960):

'A storage process ordinarily involves erasure also, to assure that old information is out of the store before new information is put in. Otherwise new information and old would be inextricably merged in the store.'

Without going further into the question of the precise model which might best describe these phenomena of inertia, an experiment will now be described, which in our opinion strongly suggests a similarity between metacontrast and binocular brightness interaction.

Experiment 8, 'Monocular rivalry'

Hypothesis. We asked whether the binocular brightness interaction of Fig. 17 could be simulated in a metacontrast situation, i.e. in monocular vision. According to the just described contour and brightness processes, this can be done in the following way: The left image (**T**) of Fig. 17 is flashed to the right eye. After a short interstimulus interval the right image **I** of Fig. 17 is flashed to the corresponding area of the

same eye. The contoured area's of **I** will be strongly dominant if **I** is flashed about 100 msec after **T**. The prediction for the apparent brightnesses for the three discs A, B and C thus is as follows. Disc A has a contour in **I**; in the total situation **I** will thus be dominant, hence A will look relatively bright. B too has a contour in **I**, but is a black disc now. The dominance of **I** will lead to a dark impression of B. Disc C only has a contour in **T**. Comparing C and A, their respective luminances in **T** and **I** are alike, but for A the second stimulus can play a rôle, due to the contour in **I**, whereas this is not the case for C. The expectation therefore is that C appears darker than A. In a strict case of complementary shares C's brightness will tend to B's, but this remains an open question.

Apparatus and stimuli.

The apparatus is given in the bottom part of Fig. 25, the slides S_l and S_r represent the test and inducing fields respectively. Two band lamps project these stimuli to the right eye in Maxwellian view; the test stimulus via mirror M_1 and half-silvered mirror $M_{\frac{1}{2}}$. The moments of projection of test and induction fields are regulated by an opaque rotating disc with an adjustable small slit. This slit passes S_l and S_r in succession, the rotation speed being

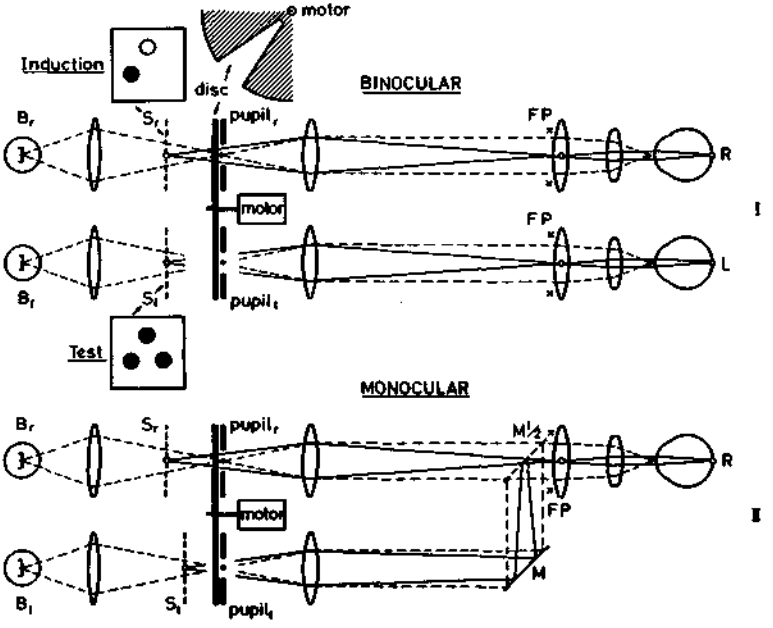


Fig. 25. Apparatus and stimuli for Exp. 8. Explanation in text.

adjustable as well. The observer's head is fixed by a head support. The slides S_l and S_r are in advance positioned such, that they coincide properly. A small illuminated fixation spot is mounted on transparent plexiglass FP in such a way that it is seen at the centroid of A, B and C. The retinal background illumination of **T** and **I** was 1000 trol, the dark discs gave 60 trol, and subtended a visual angle of 2°. The outer contour of the ring in **I** subtended the same angle, the contour width amounted to 10′.

Procedure. Ten subjects took part in this experiment. The simuli **T** and **I** were presented in the following temporal succession. **T** 10 msec., interstimulus interval 100 msec (dark), **I** 10 msec, followed by a pause of 1 sec. This succession was repeated until the observer had made his judgements.

To compare with the binocular situation, the same kind of judgement was used as in Expt. 6. The subject looked at the fixation point and judged the relative difference in brightness between every pair of stimuli on a seven point scale. Thus, three comparisons were made, A – B, B – C, and C – A. The direction and order of the scales were systematically varied over the subjects.

Results. The sum totals of the scaling scores over the ten subjects for disc A, B and C were calculated in a similar way as in Exp. 6. The maximum score for a particular disc is 140 in the present experiment, the minimum is 20. These results are given in Fig. 26.

As expected, A is by far the brightest disc. The stimulus A differs from C only in the presence of a ring in **I**. This result thus corroborates the importance of a contour in metacontrast. Nevertheless C looks brighter than B, hence the contourless field still has some masking effect.

The similarity to Exp. 6 is striking for the observer (compare the first three columns of Fig. 20b). Other patterns are also equivalent in the metacontrast and the binocular situation, e.g. the images of Fig. 21. The apparent brightness gradient in the bar again arises in the metacontrast situation, when the bar is succeeded by the hook.

More excursions into this relation lead us too far away from our theme; only one other point has still to be stressed. Alpern (1953) noted that he was not able to reveal any trace of binocular metacontrast for a limited range of stimulus conditions, i.e., for **T** in one eye and **I** in the other one. Other authors did find binocular metacontrast, e.g. Stigler (1926) and Werner (1940). To control these findings, we projected our **T** and **I** on corresponding places of left and right eye, by introducing a small change in the apparatus as indicated in Fig. 25 (upper

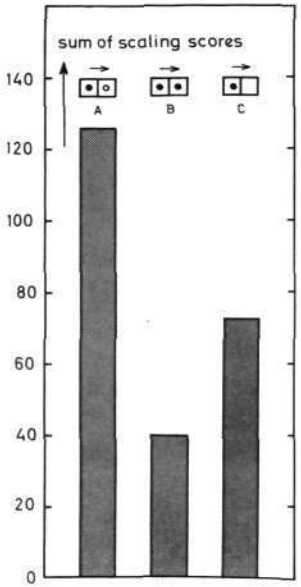


Fig. 26. Results of Exp. 8. Sum of scaling scores for the three stimulus successions.

part). Under otherwise exactly the same conditions as in Exp. 8, we did not find any essential difference in this experiment, metacontrast was operative in the same way as in monocular vision. For control we inversed the order of **T** and **I**; as in the monocular case, the second stimulus should be dominant, i.e. the discs had to appear about equally dark. This was in fact the case, three black discs being visible. The binocular metacontrast only seemed less dependent on interstimulus time. This binocular metacontrast suggests central localization of the effect, but further experiments are wanted to show a common genesis of metacontrast and binocular brightness interaction.

CHAPTER V

ALTERNATION

§ 1. Perceptual conflict and alternation

In Chapters III and IV an attempt was made to formulate the rules underlying binocular brightness interaction. The experimental results could be expressed in terms of two fundamental mechanisms. The first is the mechanism of binocular brightness averaging: binocular brightness is constant if the sum of weighted monocular energies is constant. The weighting coefficients, conceived of as reflecting the proportional shares of the eyes, are dependent upon eye dominance and upon the presence of monocular contours, but in all cases they add to unity. This was named *the law of complementary shares*. Moreover it appeared that these coefficients are quite constant as long as the contour information does not change. This has been called *the constancy rule*. The second mechanism is *the contour mechanism*. The experiments suggest the rule, that in the immediate neighbourhood of a monocularly presented contour, the binocular brightness impression is exclusively determined by the luminance of this monocular field. More precisely: the weighting coefficient tends to unity as the distance to the contour tends to zero. These mechanisms were expressed diagramatically in Fig. 11.

It is easy to show that these two mechanisms necessarily come into conflict when two non-corresponding but adjacent contours are presented to the eyes. Within a binocular area **T**, these contours give rise to a conflict in the partition of the weights. The contour in the left field produces a tendency for w_l to increase in area **T**, the non-corresponding contour in the right eye in its turn, will produce a tendency for an increase of w_r; in both cases on the basis of the contour mechanism. But an increase of both w_l and w_r would obviously violate the law of complementary shares: w_l and w_r would not longer add up to unity. This is the situation of binocular contour rivalry. From the interaction of two rather simple mechanisms it can thus be concluded

that a perceptual conflict should arise in the complex binocular situation where there is proximity of non-corresponding contours.
Apparently the conflict is resolved by the abrogation of the constancy rule, in such a way that the first tendency – increase of w_l – triumphs over the other – increase of w_r – for some time, after which the position is reversed. The law of complementary shares is thus saved by an alternating process. In terms of the diagram of Fig. 16: if non-corresponding contour information is put into the two channels, the balance B starts oscillating between its two extreme positions. During the time that w approximates 1 for one of the eyes (and we showed that this may take place near a contour), the share of the other eye is so small, that the brightness gradient of its contour is wholly obscured by the large share of the field of the other eye.

§ 2. A model for the alternation process

Breese (1899, 1909) was the first to measure what had already long before been described by a number of authors, namely that the alternation process in binocular rivalry may be influenced in a number of ways. Since Breese, two features of the process have generally been studied. The first is the alternation frequency, as a function of variables such as field luminance or degrees of contrast or colours of the stimuli. The second one is the dominance of one of the half-images over the other (i.e. the part of the total viewing time in which the right, or the left stimulus is visible) as related to similar stimulus variables.
Although a lot of work – which will be summarized in the next section – has been done in these fields the literature shows two major shortcomings. Firstly, although the effect of a number of variables on the alternation process has been studied, there has been little attempt to propose underlying mechanisms, which might explain how different variables can produce very similar effects. For instance, the fact that alternation rate can be reduced either by a decrease of the luminance of both stimuli, or by introducing blur in the stimuli, has never been attributed to one underlying process. The only attempt to unify these data was to subsume them under one heading: they were all instances of variation in 'stimulus strength', but insight in the determinants of this stimulus strength is absent.
A second shortcoming is that the results on alternation frequency are never related to those on dominance. Nobody has ever proposed a model, which unifies both aspects of the same alternation process.

In this section suggestions are made to fill in these gaps. Firstly, a new assumption as to the determinants of stimulus strength will be introduced to unify the effective variables, and next a model will be given to describe the alternation process of binocular rivalry in both its frequency and dominance aspects.
It should be remarked that the merits of this model are independent of right estimates of the determinants of stimulus strength. The model only states the relationship between dominance and frequency in the alternation process. For instance, stimulus variation A appears to affect alternation frequency when applied to both monocular stimuli, therefore A is a variation in stimulus strength. The model, then, predicts particular changes in dominance and rate of alternation, when the same stimulus strength variation A is applied to only one of the monocular stimuli. It is, therefore, irrelevant for a test of the model to know in advance which stimulus variations are variations in stimulus strength and which not.
Nevertheless, we shall need independent information about the fundamental determinants of stimulus strength in order to unify similar effects of different variables to be found in the literature. Such assumptions about determinants of stimulus strength will lead to testable deductions, if applied to the model. The next paragraph reviews the literature from the point of view of such deductions, and in § 4 we report a number of experiments of our own in this connection.

Stimulus strength. We assume that the dominance and frequency features of the alternation process are determined by a variable,which will be called 'stimulus strength' (λ). The stimulus strength of a monocular test field at some point of the binocular field is defined as the power of contralateral suppression of the test field in that point.
Our first task is to find independent operational anchorage for this definition. Can we know in advance which stimulus factors determine suppressive power of a pattern at some point? This question may be answered by starting from the obvious assumption that stimulus factors determining dominance in binocular brightness averaging (expressed in terms of w_l and w_r) are also determinants of dominance in binocular alternation (expressed in terms of visibility times of left and right eye stimulus). In the averaging experiments we found that shares of both eyes in binocular vision are constant as long as no change in contour conditions occurred. The share of an eye at the fixation point changed when the mean distance between fixation point and

surrounding contours was changed (Exp. 5). The effect of a contour appeared to decline with distance. This, then, is our first anchorage for the determination of stimulus strength: Stimulus strength in a point is assumed to be inversely related to the angular distance from the contours in the test pattern. As we never measure the dominance in only one point of a test pattern, but of the pattern as a whole, this relationship may be restated as: The stimulus strength of a pattern is assumed to be a monotonic increasing function of the *amount of contour per area* in that pattern. Furthermore, our averaging data suggest that the share of an eye is small for faint contours (compare 'tails' of Figs. 8-13). This is the second operational anchorage: we assume that stimulus strength of a pattern in binocular alternation is directly related to the 'strength' of its contours. The physical intensity of a stimulus is conventionally defined as the ratio of stimulus- to threshold-value. The equivalent definition of *contour strength* is the ratio of physical contrast to the difference threshold. Starting from such a soncept of contour strength, a large number of stimulus variables can be conceived of as special cases of contour strength variation. There are, then, two obvious ways of increasing contour strength: firstly, by increasing physical *contrast*, and secondly by reducing the difference threshold. As known, this threshold depends on a large number of conditions. We shall mention only a few of them which are pertinent to the review of the next section. The difference threshold decreases with increasing *luminance* of the test object, but beyond a certain level ($\approx$20 trol) it is about constant. For very high luminances a slight increase is often measured (Dubois Poulson 1952, p. 83). The difference threshold rapidly decreases with the degree of *eccentricity* of the stimulus. Difference thresholds are smaller for larger *size* of test object. The difference threshold increases if *blur* is introduced in the contours (see e.g. Ogle 1961). And when the contrast is a combined colour- and luminance-contrast, our measure for contour strength is equivalent to the distance of the two colours in the colour space. This distance depends, in a complex way, on the *state of colour adaptation* of the eye.

Summarizing, the operational anchorage of the stimulus strength definition is based upon observations on brightness averaging. It is twofold: stimulus strength of a test field is assumed to increase with the amount of contour per area and, for a constant amount, with the strength of these contours. Each of these two determines only an ordering of stimulus strengths. So our concept of stimulus strength

is used up to order relations, whereas ordering is indefinite if amount and strength of contours are simultaneously varied. However, this last situation is not met with in the literature. The conditions of all experiments are scalable along such a dimension of ordered stimulus strength. The alternation model, which will now be developed, will therefore also be checked up to order relations. This does not exclude that it may eventually lend itself equally well to the use of a metric parameter.

The alternation model. In Exp. 5, Chapter IV, it appeared that $w \approx 1$ is reached, for a sufficiently small test field, if a homogeneous uncontoured field is presented to the other eye. In this situation a completely stable state is attained. There are no 'saturation effects' in the sense of spontaneous disappearances of the small test field in favour of the homogeneous field (if Troxler's effect is prevented, i.e. by foveal presentation of the stimulus). This is to a large degree independent of the stimulus strength of the test target. Variations in contrast or luminance do not change the central fact, that the perception with one eye continues without interruption as long as no rival contour is presented to the other eye.

This fact may have important implications for a model of binocular alternation. I.e., it is plausible, that the mean period during which one of the stimuli is visible in binocular rivalry is a function not of the strength of the same stimulus, but only of the strength of the contralateral stimulus.

Before going into details, we shall introduce some symbols. $\bar{t}_r$ will denote the mean time during which the right stimulus is uninterruptedly perceived, and likewise $\bar{t}_l$ denotes the mean period length for the left stimulus. We shall use these terms only in relation to the two-choice rivalry task, hence $\bar{t}_r + \bar{t}_l = \overline{T}$, the mean duration of the complete cycle. The predominance of a stimulus is defined as the percentage of the total viewing time, during which this stimulus is perceived. S_r and S_l mean left and right stimulus respectively, and λ_r and λ_l will stand for right and left stimulus strength.

Our verbal statement now becomes in symbols $\bar{t}_r = f(\lambda_l)$ and $\bar{t}_l = f(\lambda_r)$ both in the sense that $\bar{t}$ is a monotonic decreasing function of λ. Before deducing some propositions from this assumption, the idea may be restated alternatively: if S_r is perceived, the conditional probability that during some time interval t, S_l becomes visible, depends only on λ_l, not on λ_r, and inversely for a $S_l \rightarrow S_r$ change.

The precise characterstics of the distributions of t, or the function $f(\lambda)$ will not be discussed at this stage of the argument, but will be delt with in § 5. Even with $f(\lambda)$ unspecified it is possible to deduce four testable propositions on predominance and rate of alternation from the above assumption.

I. *Increase of the stimulus strength in one eye will increase the predominance of the stimulus.*

Deduction of the proposition for S_r: The predominance of S_r is $100\, \bar{t}_r/\bar{T}\% = 100\, \bar{t}_r/(\bar{t}_r + \bar{t}_l)\%$, but $\bar{t}_l = f(\lambda_r)$, so an increase of λ_r leads to a reduction of the denominator, and this means an increase of the predominance of S_r.

II. *Increase of the stimulus strength in one eye will not effect $\bar{t}$ for the same eye.*

This is a negative but important statement: $\bar{t}_r$ can only be affected by λ_l, not by λ_r.

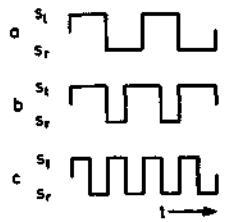
III. *Increase of the stimulus strength in one eye will increase the alternation frequency.*

Increase of λ_r reduces $\bar{t}_l$, and leaves $\bar{t}_r$ unaffected, hence $\bar{T} = \bar{t}_r + \bar{t}_l$ is reduced, and this is equivalent to an increase in rate of alternation.

IV. *Increase of the stimulus strengths in both eyes will increase the alternation frequency.*

Increase of λ_l and λ_r leads to reduction of both $\bar{t}_l$ and $\bar{t}_r$, and hence of $\bar{T}$.

The propositions are visualized in Fig. 27.



a. $\lambda_l = \lambda_r \rightarrow \bar{t}_r = \bar{t}_l$

b. increase of λ_l only → reduction of $\bar{t}_r$ and increase of frequency

c. increase of both λ_l and λ_r → reduction of both $\bar{t}_r$ and $\bar{t}_l$ and increase of frequency.

Fig. 27. Diagram of the alternation model. Effects of variations in stimulus strength.

We will at first be concerned with qualitative data from literature (§ 3) and our own experiments (§ 4), pertinent to the propositions I to IV. Further quantitative insight into the process and possible underlying mechanisms will be suggested only after the presentation of the experimental data in § 4.

§ 3. Literature data on alternation rate and dominance

As most of the literature on binocular rivalry is concerned with alternation rate and dominance, an investigation of the alternation model should of course start with what is already known about the subject. Moreover, this provides the opportunity to systematize the discussion of otherwise rather unrelated findings.

The vast majority of the reported experiments are of the dominance-type. For one eye, the stimulus conditions are varied, and the effect on the predominance of that stimulus is measured. A smaller part of the literature is concerned with simultaneous changes of the conditions in both eyes. These studies normally give data on alternation rate. A minority of the studies give data on rate of alternation for the situation in which the stimulus presented to one eye is varied.

As the model relates both aspects of the alternation process, rate and dominance, we will not follow this division, but only add in brackets the number of the proposition (I to IV), relevant to the experiment in question. The assumptions about determinants of stimulus strength gave rise to deduction of a number of variables which are special cases of stimulus strength variation. The present review is ordered according to these variables.

In most experiments contour strength is varied, sometimes by varying contrast, sometimes by varying the difference threshold. We are first concerned with the *contrast* experiments.

Roelofs and Zeeman (1919) were the first to stress the importance of contrast in binocular rivalry. They showed with the orthogonal grids stimulus (Fig. 1), that a monocular decrease in grid contrast reduced the dominance in rivalry of the eye concerned, irrespective of whether the white background was darkened, or the black bars were increased in luminance, thus irrespective of the total amount of light energy (I).

Gellhorn (1924 a, b, c, 1925 a, b) presented a red, green, yellow or blue square on a grey background to one eye, and a grey square on a grey background of variable luminance to the other eye (on corresponding places). He found that the dominance time of the grey square was

directly proportional to the luminance difference between square and background. (irrespective of the sign of the difference). (I).
Mull, Armstrong and Telfer (1956) used stimuli similar to Gellhorn's, namely a red and a blue square on a neutral background. They varied the contrast of the stimuli, by using a grey or a black background. This did not notably affect the alternation rate. It is however not possible to reconstruct what change in contrast took place by changing the background. Probably the contrast was simply reversed (III). Alexander (1951) and Alexander and Bricker (1952) used orthogonal grids of black bars as stimuli. They varied the luminance of the grey background between the bars and measured alternation rate. The background reflectance was varied from 10 to 90% in 20%-steps,

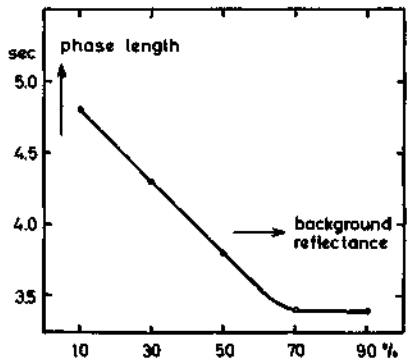


Fig. 28. Contrast and proposition IV. From Alexander and Bricker's data.

whereas the bars had a constant reflectance of 1.4%. The contrast was thus always above 95%, except for the 10%-background. This produced an unfortunately graphic demonstration of the relationship between contrast (linear scale) and alternation rate. In Fig. 28 the mean rate for their subjects is replotted directly against background reflectance and is shown to be remarkably strongly influenced by slight variations in reflectance. The results agree with proposition IV. Kakizaki (1960), using an orthogonal grids pattern (bright bars on a dark background) varied the contrast of bars and background for one eye by increasing the luminance of the bright bars (the background was kept constant). He found an increasing predominance for increasing contrast (I). Predominance had however a limit at about 64%. It could again be reduced by increasing the contrast of the other

grid (I). The predominance did not differ significantly from 50% as long as both contrasts were equal. The rate of alternation increased with increasing contrast of one grid (III). It seemed that for extreme contrast differences of the two grids, the rate of alternation decreased. One possibility is that the pupil size in both eyes is so much reduced by the high luminance of the bars in one eye, that the low contrast in the opposite eye is simply no longer visible. Kakizaki did not use artificial pupils in his experiments. Kakizaki himself suggests that the contrast used for one eye was at threshold level. In a comment on a similar experiment, in which a 100% predominance of one grid was obtained, he ascribed the effect in fact to the invisibility of the other grid. In this latter experiment he used black bars on a circular white background. The use of black bars makes it impossible to speak in terms of contrast, but changes in background illumination induced over-all effects, equivalent to the contrast changes in the former experiment.

The inverse pattern (bright bars on a black background) was used by Kaplan and Metley (1964). They varied the luminance of the bars. Increase of the luminance of one bar from log trol = 0.5 to 5 leaving the other one constant (log trol = 0 or 5), led to a maximal dominance approaching 100% (I). Nevertheless alternation occurred even when the two fields were very different in brightness. The authors also noticed an increase in rate when the illumination of only one field is increased (III), except for the case of complete dominance which could occur with extreme luminance differences. However they do not present data on this point. Another finding is a general increase of rate with increase of illumination in both eyes up to some level (about log trol = 1.2) (IV). A further increment of luminance above log trol = 4 slightly decreased the rate. This accords fairly well with the often measured slight increase of difference threshold at high luminances (probably due to saturation effects).

As to the *amount of contour per area*, Alexander (1951) found a lower alternation rate when gaps were introduced in the bars (the bars were replaced by dotted lines). The effect of this reduction in the amount of contour per area is in agreement with proposition IV.

The results of Allers (1935), mentioned in connection with Wilde's theory (Chapter II) should be placed in the same context. He replaced one grid of the orthogonal grids stimulus (Fig. 1) by a wave pattern (waves in stead of straight bars), and found the wave pattern to be more dominant than the initial bar pattern. Introduction of waves

also increases the amount of contour per area (as Wilde rightly remarks), and the result agrees with proposition I.

A similar example is to be found in Gellhorn's work (*op. cit.*). In his experiments on colour adaptation and rivalry – which we will presently describe – he presented a blue square to the left eye and a yellow one to the right eye (on the corresponding place). He now introduced a yellow additional stimulus in the left field near to the blue square, and found that the blue square became more dominant. Gellhorn initially thought in terms of some action of the complementary yellow on the blue, but found the same effect when the additional stimulus was not of the complementary colour. Moreover, the dominance-shift produced by the complementary additional stimulus could be counterbalanced by a similar additional stimulus presented to the other eye, irrespective of its colour. Gellhorn could not find an explanation for this unexpected result. The probable explanation is, that the contours of the introduced additional stimulus, if presented near enough to the main stimulus, have a 'radius of action' which extends over the main stimulus, and so increase its strength. The lack of dominance effect when additional stimuli are introduced in both eyes is than due to the simultaneous presentation of extra contours in both eyes, and has nothing to do with colours. In the next paragraph an experiment is reported which tests the effect of an additional stimulus.

A direct test of the radius of action of a contour has been performed only by Kaufman (1963). He presented a horizontal bar to the left eye and two vertical bars to the right eye, so that the binocular impression was an intersection of a horizontal and two vertical lines. The observer pressed a key whenever the part of the horizontal bar between the vertical bars disappeared. The amount of suppression appeared to be a function of the angle of separation (θ) of the two vertical bars (I). Complete suppressions of the line segment hardly occurred beyond $\theta = 2°$. We may translate this in terms of weighting coefficients: no $w \approx 1$ is produced for area's in the right eye at more than about 1° distance from a contour. Kaufman also found a monotonic increase in alternation rate with a decrease of θ (III).

There is not much unanimity on the rôle of *luminance* per se in rivalry. The results of experiments in which a constant (and finite) contrast was used at different luminance levels are rather divergent. This is not surprising, because the difference threshold is a curvilinear function of luminance. For low luminance levels a small luminance change

corresponds with a large change in threshold, and hence with a large change in contour strength. For higher luminance levels, the threshold is nearly constant. For high levels even a slight increase in threshold is often measured. The divergence of the results may be due to the differences in the luminance levels chosen.

Breese (1899, 1909) found that an increase of the luminance of his orthogonal differently coloured grids, increased the alternation frequency (IV). Moreover the dominance ratio shifted to 3 : 2 when the luminance ratio of the two fields was changed to 4 : 1 (I); there is, however, nothing known about the absolute luminance levels he used.

The same applies to the results of Roelofs and Zeeman (1919). These authors found no important effects in variations in the total luminance level, but Mull, Armstrong and Telfer (1956) obtained a doubling of alternation frequency by replacing the 15 watt lamp, illuminating their stimuli (differently coloured squares on white backgrounds) by a 200 watt lamp (IV). None of these authors give absolute values for the luminances used.

In the next paragraph an experiment is reported in which the effects of contrast and luminance are compared.

The difference threshold changes with *eccentricity* of the test target. It was again Breese who presented the first data on this variable. With his orthogonal grids pattern he found that alternation rate decreased towards the periphery of vision (IV).

Wilde (1938) used a pattern of two crossing bars to study the effect of eccentricity. Although his subjects showed strong individual differences, he found a slight tendency for a reduction of the alternation rate towards the periphery (IV).

However the problem with this variable of peripherality is that it interferes with Troxler's effect. The slowing down of the rate to be expected from our model when the stimuli are shifted more and more towards the periphery of the visual field will be counteracted by the increase in spontaneous disappearances in either eye under the same conditions. As both processes are thus correlated with peripherality, it is not possible to test the effects of the present variable until more quantitative data emerge on the importance of this factor in both mechanisms.

Gellhorn and Schöppe (1924b) give some results concerning rivalry between extrafoveally presented coloured squares. It is however impossible to make even rough estimates of the combined colour and

luminance contrasts of their stimuli. The picture is much complicated by the fact that the authors do not present data on the luminance of the background (white or black), on the eccentricity of their stimuli in visual angles (in view of the chromatic thresholds), and of the brightness of their colours. As to this last point: they presented so-called peripheral values, making a peripheral comparison of their colour and different greys. Their assumption of a difference in threshold shift for different colours as the periphery is approached is not in accordance with their use of this peripheral values technique. Flicker-photometry was well known in 1924. So they could have made a better approach.

Variations in *size* of the test target have been studied only by Breese (*loc. cit.*). He found a reduction of cycle length when the size of his grids was increased (IV). This effect was, however, most marked for small sizes (up to 10 mm-square). Unfortunately, visual angle values cannot be reconstructed for comparison with difference thresholds as a function of target size. The difference threshold does not change much beyond 1° visual angle.

Adaptation–variables have been studied only by Gellhorn (*loc. cit.*). The general type of experiment was as follows: two differently coloured pentagons on grey backgrounds were presented to corresponding places of the retinas. One of the stimuli was however preceded by an adaptation field, a homogeneously coloured bright field, to be fixated during 1-3 minutes. If this unilateral adaptation field had the same colour as the pentagon for that eye, Gellhorn found reduced predominance of this pentagon in rivalry (I). This may be understood as a contrast-reducing effect of the adaptation field. In terms of colour space: both pentagon colour and neutral grey are shifted away from the adaptation colour, but the shift of the pentagon colour in the direction of the white point is larger than the shift of the grey away from it. The contrast is thus reduced. This is the only fairly stable result of Gellhorn's experiments. For other colour combinations the effect seemed rather unpredictable to him, and his data on the precise characteristics of his stimuli are insufficient to translate them in terms of shifts in colour contrast.

Blur-effects were again initially studied by Breese (*loc. cit.*). In one of his experiments he blurred the contours of the grids in both eyes by out-of-focus projection. In this way presumably not only blurring of contours is introduced, but also reduction of contrast. Hence, it is not certain whether the reduction of the alternation rate he found

(IV), should be attributed mainly to the effect of blur on the difference threshold. An experiment on blur in rivalry, in which contrast is kept constant, is reported in the next section.

This short excursion into the literature did not aim at historical completeness, nor did we go into details of the theoretical backgrounds which gave rise to some of these studies (e.g. comparison of physiological and psychological inhibition by Breese, Hering's assimilation-dissimilation theory in Gellhorn's experiments, and Hull's stimulus intensity dynamism in the case of Kakizaki). We sought only for confirmation or counter-evidence for the proposed alternation model. The booty of the expedition can be parcelled as follows:

1. Proposition I has often been the subject of experimentation and has generally been confirmed, but a simple check of this proposition has more to say about the usefulness of the concept of stimulus strength than about the internal consistency of the model. A check on this consistency is only possible if the stimulus variable is also tested in its effects in the area of the other propositions. Examples of this experimental situation were given in the work of Breese, who found the predominance-effect (I) and the rate–effect (IV) when respectively a monocular and a binocular increase of stimulus luminance was introduced. The same was found by Kaplan and Metlay, and these authors, moreover, found rate increase when the luminance of only one stimulus was increased (III). Kakizaki found the I- and III-effects for uniocular increase of contrast, and finally Kaufman's data show the I- and III-effects for the contour-per-area variable. These studies confirm the internal consistency as far as propositions I, III and IV are concerned. But as for the more specific proposition II, no data are available at all. On the contrary, one generally meets the opinion that the mean duration of a dominance period is increased by strengthening the stimulus under concern.

2. Stimulus strength has been assumed to be directly proportional to contour strength, i.e. the ratio of contrast and difference threshold, and as directly proportional to the amount of contour per area, in view of the 'radius of action' of a contour. We did not find striking counter-arguments against the use of these parameters, but this does not testify to its accuracy. More data are needed. Data can firstly be obtained by varying the ratio of contrast and difference threshold. There are two obvious ways to increase this ratio: *a.* by increasing contrast, and *b.* by decreasing the difference threshold. Furthermore, the effect of the 'radius of action' of a contour can be tested *c.* by variation of the angu-

lar distance between stimulus contour and target in the other eye. In the next paragraph these three components of stimulus strength will be studied in one type of stimulus; first the distance aspect, then the effects of contrast and threshold variations. The latter two experiments are, moreover, designed to study proposition II in relation to I and III. The only point of clear controversy in the literature was on the effect of absolute luminance level of the stimuli. Roelofs and Zeeman found that this variable had no effect, whereas Breese and Mull *et al.* obtained changes in alternation in changing the illumination of their stimuli. From our definition of contour strength, no change is expected as long as the ratio of contrast and difference threshold is constant. The threshold is approximately constant for luminances beyond about 20 trol. At this level of illumination the effect of luminance changes is virtually negligible. This will also be checked in one of the following experiments.

§ 4. Experiments on the alternation model

Experiment 9. Radius of action I

Problem. Like Kaufman we were interested in the range of the suppressing effect of a monocularly presented contour. This question is not equivalent to that investigated in Exp. 5, Chapter IV. There the problem was the decline of the contour effect in binocular brightness averaging; i.e. the reduction of w for increasing field size. Our present problem is: how large can the angular separation between a left eye- and a right eye-contour be in order still to provoke moments of complete suppression of one of them in binocular vision. In terms of weighting coefficients: up to what angular separation can $w \approx 1$ arise? Kaufman found a maximal angle of about 1° ($\theta = 2°$) for foveal vision. A constant level of about 50% predominance was reached for $\theta = 14'$ and smaller. No data are known for peripheral vision.

Stimuli. The stimuli used are given in Fig. 29. The black squares were fused binocularly. In this way the white left test point is prevented from drifting within the white right circle. The ring and the test point had a constant luminance of 200 cd/m². We used a ring as 'suppressing' stimulus to have a constant left contour – right contour distance in all directions.

Procedure. The total disappearance time of the left test spot during a one-minute observation is measured as a function of the inner diameter

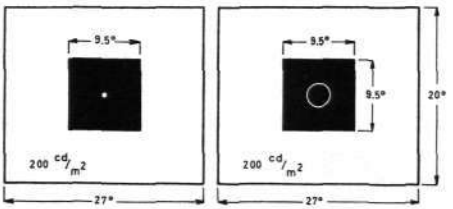


Fig. 29. Stimuli used in Exp. 9. The left point stimulus had a diameter of 20′ (luminance: 200 cd/m²). The right 200 cd/m²-circle had a variable inner diameter and a contour diameter of 6′.

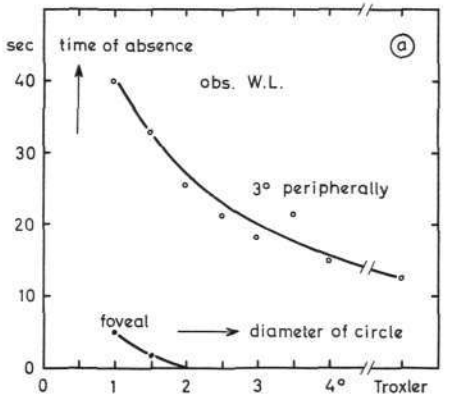
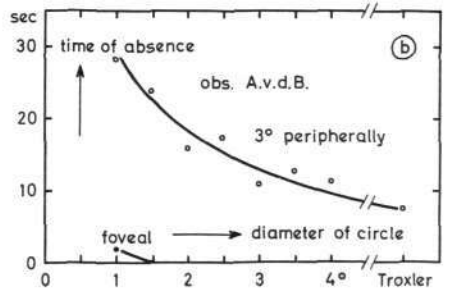


Fig. 30ab. Suppression of left test spot as a function of the diameter of the right circle for central and for peripheral vision (Observers W.L. and A.v.d.B., respectively).



of the surrounding circle. The diameter was varied in 0.5°-steps from 4° to 1°. Furthermore the condition of 'no circle' was tested, to have a comparison with Troxler's effect. The experiment was carried out using central fixation, i.e. fixation of the test spot, and also peripheral fixation; in the latter case an extra fixation point was introduced in both eyes at 3° above the test spot. The measurements were started with Troxler's condition, followed by a descending series of circle diameters. Two subjects took part in this experiment.

Results. The results are shown in Fig. 30. The radius of action is much larger for peripheral than for foveal vision. For a 3.5°-circle, it is distinctly above the Troxler level in peripheral vision, whereas in foveal vision complete suppression only occurs for 1°-and 1.5°-circles. For all other diameters $w \approx 1$ never arises (although nearly complete suppressions often occur). It should be remembered that in Exp. 5 $w \approx 1$ also only occurred for the 1°-case. It is not surprising that complete suppressions do not occur beyond the area within which complete dominance was possible in the averaging experiments. If we take experimental differences into account, our results for foveal vision are in fair agreement with Kaufman's, as to the maximal extent of complete suppression. We come back to these results in § 6. As to the model: in this experiment proposition I is confirmed as to peripherality of vision and radius of action as stimulus strenth components.

Experiment 10. Radius of action II

Problem. Gellhorn's experiment raised the question of whether addition of contours near the stimulus in one eye should increase the predominance of the stimulus in rivalry. From the 'radius of action'-way of thinking, we should expect such an effect if the additional stimulus is sufficiently near to the main stimulus.

Stimuli. The stimuli for the two conditions of this experiment are given in Fig. 31. The 6°-circular white backgrounds in both eyes induce correct fusion of the images. The black 1.5°-spot of the right eye precisely coincides with the 1.5°-white spot of the left eye. This stimulus has many advantages above the classical crossing-bars or orthogonal grids stimuli: it is always clear whether one sees white on black or black on white. Partial inhibition of a contour, in which the subject has the problem of setting some criterion, never occurs. Furthermore

the contour-interaction is constant along the contour, which is not the case with the classical stimuli. The tendency of the spots to drift apart is wholly prevented by mounting them in equivalent surrounding fields.

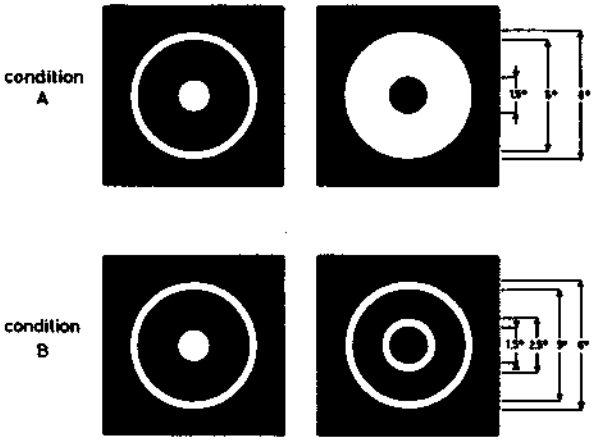


Fig. 31. Stimuli of Exp. 10. In condition B an extra contour is added in the right field.

Procedure. The hypothesis is that the extra ring used in condition B induces a larger predominance of the black right spot, than it has under condition A. Six subjects observed for twelve one-minute periods during which conditions A and B alternated. Half of them started with A, half of them with B. They were instructed to press a key as long as the black on white situation was perceived.

Results. The mean predominance was 37.1% under condition A. This increased to 42.1% under condition B. In an analysis of variance this difference just fell short of significance at the 5%-level. Hence the conclusion is that there exists a tendency in the expected direction, but the effect is not very strong under the present conditions. The question from Gellhorn's experiments thus remains unanswered, the more so as the angular separation of his main and additional stimulus is not known.

We now come to the main experiments, in which the relation between propositions I, II and III of the alternation model are tested. In the first experiment contour strength is reduced by increasing the differ-

ence threshold (introduction of blur). In the second one it is reduced by decreasing contrast. In this last experiment, the absolute luminance level is also varied, without changing contrast.

Experiment 11. Blur

Problem. Blurring the stimulus in the left field should reduce its contour strength. The effect of this reduction should be a reduction of the predominance of the left stimulus (I), and reduction of the alternation rate (III). But the mean dominance time $\bar{t}_l$ of this stimulus should not be affected (II).

Stimuli. The stimuli are presented in Fig. 32. The blur-condition B was effectuated by placing an extra lens in the left light pathway and by adjusting P_l and P_b (see Fig. 6; different filters could be placed in the pathways of P_b) so as to obtain the luminance distribution, shown in Fig. 33.

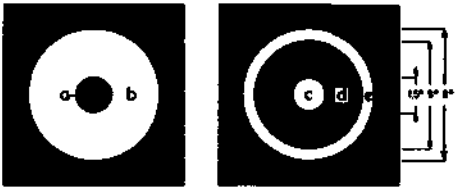


Fig. 32. Stimuli of Exp. 11 and 12.
For Exp. 11: a = 40 cd/m², b = 400 cd/m², d = 23 cd/m² and c, e = 400 cd/m².
For Exp. 12:
Condition A: a = 85 cd/m², b = 710 cd/m².
Condition B: a = 85 cd/m², b = 100 cd/m².
Condition C: a = 12 cd/m², b = 100 cd/m².
All conditions: c = 100 cd/m², d = 5.75 cd/m², e = 100 cd/m².

As a comparison the luminance distribution under condition A is also represented. Both were measured by means of a photomultiplier. Moreover, the total amount of light from an area, somewhat larger than a (see Fig. 32), but including it, was measured under condition A and B. No difference could be measured. So, under the present conditions the introduction of blur did not affect contrast or total amount of light of the left stimulus.

Procedure. As in all other experiments reported in this chapter, the subject looked through circular 1mm-pupils and fixated the centre of **a** and **c** (Fig. 32). He kept the key depressed for as long as the left stimulus was dominant (black on white). Ten subjects took part in the experiment. Each subject underwent four one-minute inspection sessions: two of stimulus complex A and two of B. The order of these four sessions was randomly determined.

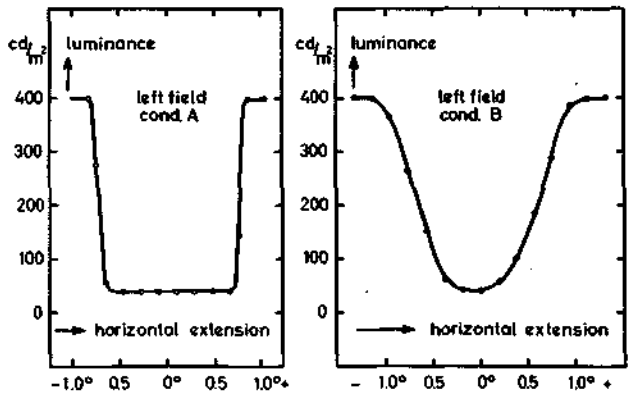


Fig. 33. Luminance density of the dark spot in the left field of Fig. 32 for the non-blur and the blur conditions, Exp. 11.

Results. Two analyses of variance were undertaken: one on the dominance scores, and one on the frequency scores. As to the dominance scores, the mean predominance for the ten subjects in the sharp condition was 50.9% (or 30.55 sec per minute). For the blurred condition, it was 26.5% (15.87 sec). The difference is significant at the 0.001-level, and confirms proposition I. The mean frequency scores for the A and B conditions were 12.20 and 6.40 per minute respectively. This difference was significant at the 0.005-level, and agrees with proposition III.

As to proposition II: the mean $\bar{t}_l$ was 2.50 sec in the A-condition, and 2.48 sec in the B-condition. No analysis of variance needs to be performed: $\bar{t}_l$ is not affected as long as the right stimulus strength is constant.

Experiment 12. Contrast

Problem. This last experiment serves a number of purposes. Firstly we wanted to compare contrast variation and luminance variation

in their effect on rivalry. The prediction is that, for a sufficient level of luminance, luminance variations will have negligible effects on the rivalry process, but we expect a large effect of variations of contrast. Secondly, separate analysis of predominance and frequency data will give information about propositions I and III. And finally, calculations of $\bar{t}_i$ will provide another test of proposition II.

Stimuli. Except for their luminances, the stimuli are the same as in the former experiment. Values are given in the caption to Fig. 32. Three conditions were employed. In conditions A and C, the contrast of the left test spot is 7.35, but the stimuli differ in the total level of luminance The luminance of the left field in condition A is 7.1 times its luminance in C. In condition B, the contrast is much less then under the other two conditions (0.18), but the luminance level of the stimulus is in between those of the A and C stimuli. In fact, the test spot has the same luminance as under condition A, and the surrounding field has the same luminance as under condition C. In this luminance region the difference threshold is fairly constant. The right field is kept constant throughout the experiment.

Procedure. Ten subjects were presented with the three conditions in random order. This order was repeated once, giving six one-minute observation periods per subject. The subject was instructed to push the key for as long as the black on white test spot was visible.

Results. As in the former experiment, two analyses of variance were calculated, one on the predominance scores and one on the frequency scores. The predominance of the left field for condition A was 41.9% (25.13 sec) on the average, for B it amounted to 27.6% (16.55 sec), and for C 46.6% (27.93 sec). For a comparison between these means we used Scheffé's method. It revealed that the differences between B and A and between B and C were significant on the 0.001-level. The small difference between A and C is not significant.
These results corroborate Roelofs and Zeeman's finding, that luminance level is rather immaterial to dominance in binocular rivalry, as long as contrast is preserved. The effect of changes in contrast appears to be important in that the low contrast in B resulted in low predominance for the left field (I).
The analysis of frequency scores showed again significant differences between conditions ($p < 0.001$). Mean frequency under condition A

was 9.6, under B 6.4, and under C 10.9. Again, only the differences B-A and B-C are significant ($p < 0.001$). This is in agreement with proposition III.

As to proposition II, for A, B and C we found $\bar{t}_l$'s of 2.62, 2.59 and 2.56 sec respectively, which again confirms this proposition.

In conclusion, from a consideration of the literature and the present experiments it may be stated that the assumed determinants of stimulus strength have some merits at least up to order relations, but that even at this level there are still gaps in our knowledge. For example, what are the order relations between levels of contrast on the one hand and levels of blur on the other hand? Nevertheless a number of specific predictions based on these assumptions have been possible, such as for instance on the effects of contrast and luminance variations. There is much evidence for an alternation model, based on the assumption that the mean duration of the predominance period of one eye is a function only of the stimulus strength in the other eye. Proposition II is supported by Exps. 11 and 12. The assumption moreover, generates propositions on both dominance and rate aspects of the alternation process, none of which had to be rejected.

§ 5. Statistical properties of distributions of dominance periods

Further insight into the underlying mechanism of the alternation process may be obtained by a consideration of the distribution of the separate dominance intervals. Of what t_l-distribution is $\bar{t}_l$ the mean? As a first step we calculated mean ($\bar{t}_l$) and standard deviation (s_l)

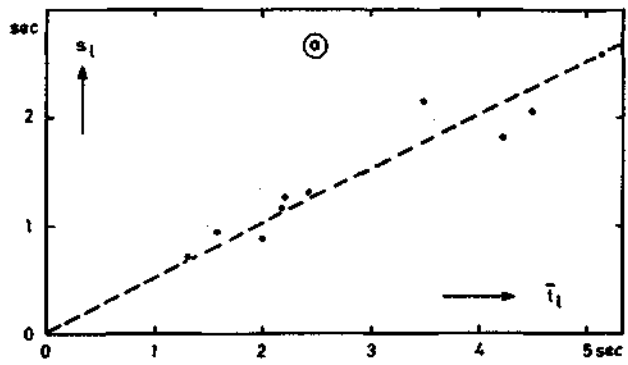


Fig. 34a. Relationship of mean and standard deviation in the blur experiment.

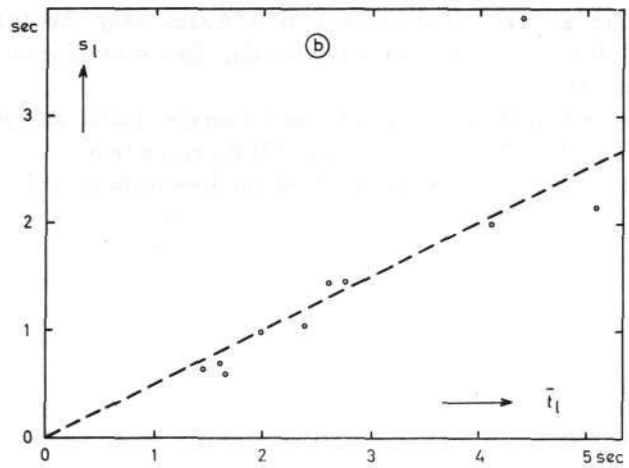


Fig. 34b. Relationship of mean and standard deviation in the contrast experiment.

over the t_l- sample of each of the ten subjects of Exps. 11 and 12.[1] Means and standard deviations are plotted in Figs 34a and 34b. It appears from these figures, that the general relation in both experiments may be expressed by $\bar{t}_l = 2\, s_l$. This relation holds fairly well for both large and small $\bar{t}_l$. This excludes the possibility of an exponential 'holding time'-distribution. If the chance of no left-right

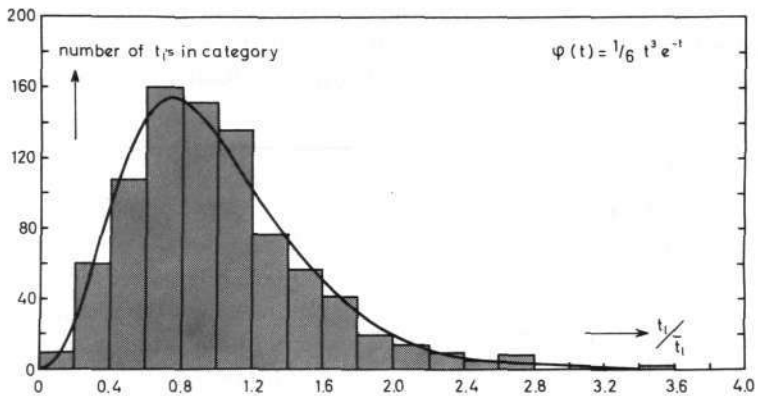


Fig. 35. Histogram of t_l-distribution ($\bar{t}_l = 1.00$), with best fitting density function.

[1] For this calculation we used only those periods of left predominance which were not bordered by the beginning or end of the one minute period of observation.

shift during t is $P_0(t) = e^{-\lambda t}$, the mean time $\bar{t} = 1/\lambda$, and also $\sigma = 1/\lambda$. This does not agree with the findings.

Because of the constant $\bar{t}_l/s_l$-ratio, we divided the t-values for each subject in each experiment by the mean $(\bar{t})$ of these values. These new t-values thus have a mean $\bar{t} = 1$. From these values one histogram of the t_l-distribution was made over the two experiments and all subjects. This is given in Fig. 35. This distribution can be approximated by a function of the form $\varphi(t) = \frac{t^{a-1} e^{-t}}{\Gamma a}$, in which $\Gamma a = \int_0^\infty t^{a-1} e^{-t} dt$ (for integers $\Gamma a = (a - 1)!$).

The t-distribution $f(t)$ of each subject, and also the one of Fig. 35 may be conceived of as deformations of $<p(t)$, in formula: $f(t) = X<p(Xt)$, in which X represents a scale factor.

The mean of the $\varphi(t)$-distribution is $\mu = \int_0^\infty \frac{t^a e^{-t}}{\Gamma a} dt = a$, the variance is $\sigma^2 = \int_0^\infty \frac{t^{a+1} e^{-t}}{\Gamma a} - \mu^2 = a$, hence the standard deviation $\sigma = \sqrt{a}$.

To fulfil the experimental requirement that $\mu = 2a$, we have $a = 4$ $(\mu = 4, \sigma = 2)$. So the best fitting $\varphi(t) = \frac{t^3 e^{-t}}{3!}$, and $f(t) = \frac{\lambda}{3!}(\lambda t)^3 e^{-\lambda t}(1)$. the mean of this distribution is $\bar{t} = 4/\lambda$, whereas its standard deviation is $2/\lambda$. We wanted to draw this function in the histogram (Fig. 35). Because the mean of this histogram has been put to unity, a scale factor $\lambda = 4$ had to be used in order to have $\bar{t} = 1$Furthermore the area under the curve was made equal to the area under the histogram. The approximation is fair, but we realize that other functions may do as well. The question is whether the function may be understood as an expression of some underlying mechanism. This section is concluded with some remarks on this point.

It has been shown that $\bar{t}_l$ is independent of λ_l, the left stimulus strength (Exps. 11 and 12). It is not accidental that in the above calculations the same term X has been used. The scale factor X in (1) may be taken as the stimulus strength of the stimulus presented to the other eye. The monotonic decreasing function $\bar{t}_r = f(\lambda_l)$ in § 2, is specified then, by $\bar{t}_r = 4/\lambda_l$; an increase of λ_l implies a reduction of $\bar{t}_r$. One possible mechanism which accounts for an effect of stimulus strength so that a function of form (1) results is a summative one in which the unperceived stimulus produces a series of randomly distributed 'excitation spikes'. If we set the chance of no spike occurring in t to $P_0(t) = e^{-\lambda t}$, the waiting time for one spike has a probability density function

$f_1(t) = \lambda e^{-\lambda t}$. The waiting time up to the n th spike can be found by applying $f_n(t) = \int_{-\infty}^{\infty} f_{n-1}(u) f_1(t-u)\, du$ (this involves the assumption that the waiting time for the next spike is independent of the former waiting times). For $n = 4$ we find $f_4(t) = \frac{\lambda}{3!}(\lambda t)^3 e^{-\lambda t}$, which equals (1). This may be interpreted in the sense that the summative effect of four successive spikes from the recessive stimulus is necessary and sufficient to regain dominance for that stimulus.

The symbol λ now represents simply the mean number of spikes per unit time. For the stimulus strengths of Exp. 11 and 12 we found I_t's of about 2.6 sec, therefore $I_t = 4/\lambda_r = 2.6$, so $\lambda = 1.54$, which amounts to an average inter-spike distance of about 0.65 sec. There are however large individual differences in λ. This inter-spike time is probably associated with 'flicks' in eye-movement, suggesting some summative effect of time-contours. At the present stage of research we are not able to give more psychophysical reasons for such a summative process. Further elaboration of the term 'excitation spike', used in this section would therefore be premature.

§ 6. Fusion and alternation

This monograph was opened with a few remarks about the mutual relation of fusion and rivalry. We want to conclude it with some more consideration of this crucial subject. In § 1 of this chapter, it was shown that the averaging and contour mechanisms are in conflict, when non-corresponding contours are presented to the eyes. So far we have considered only the case of non-corresponding, and thus non-fusing contours, but what about the normal case of corresponding contours? It must be noted that the experiments of Chapters III and IV give no reason to expect the case of corresponding contours to be different from that of non-corresponding contours. There is no strict reason to believe in a special 'fused situation', in which the weighting coefficients are suddenly $\frac{1}{2}$ for both eyes, and homogeneously over the whole visual field. On the contrary, it is quite likely that in this case, too, parts of the fields will enter into rivalry. However, one will not be aware of this, so long as the stimuli are the same.

Authors on binocular rivalry customarily extend the rivalry process to cover the situation of fused images. We have already mentioned Du Tour (1760) who claimed that rivalry is a demonstration of the fact

that we mostly see with only one eye. For more than two centuries this point of view has been voiced by a large number of authors. In this century it is Verhoeff (1935), who assumes that only one of the retinal images is present in consciousness at a time. Similar things are suggested by Asher (1953) and recently by Hochberg (1964).
We are also inclined to this view, but caution should be taken before one states that each point of the field is perceived with only one eye. Two considerations are of importance here.
1. Ogle (1950) rightly remarks that the precise meaning of fusion cannot fully be discussed, before more is known about the neuroanatomy of the visual area of the cortex. And we may add its physiology. This is indeed the direct way to get an impression of the shares of the eyes in normal binocular vision.
2. Most authors state their 'monocularism' in all-or-none terms. So for instance Verhoeff. He assumes that corresponding retinal units are represented separately somewhere in the brain, but each of every pair is represented in consciousness by the same single unit. He concludes that this conscious unit can receive the stimulus from only one retinal unit at a time, and when it receives the stimulus from one it excludes the stimulus from the corresponding unit. Asher (*loc. cit.*) assumes that one of a pair of corresponding points always suppresses the other. Hochberg (*loc. cit.*) also assumes a cyclopean field, constructed piecemeal out of the contents of one eye or the other. The question is whether such an all-or-non assumption is tenable, or whether it is better to think of different levels of dominance of the eyes for each point of the visual field.

As to the first consideration: recently, Hubel and Wiesel (1959, 1962) have thrown some light on this field. These authors studied the receptive fields of single cells in the striate cortex of the cat. The results of their study are also important for the second consideration. The authors determined the field of action of each cell and optimal stimulus characteristics by presenting different kinds of targets to one or the other eye of the cat, and simultaneously recording cell-responses. A detailed summary of their important results would take us too far afield; we limit ourselves to some of their binocular results. It appeared that 84% of the cells studied had receptive fields in both eyes. A small number of these cells could only be activated by simultaneous stimulation of both eyes, but most could be activated from either eye alone. The receptive fields of a given cell were similar in

both eyes, but it seemed to be the rule that one of the eyes had a dominant effect in the activation of the cell; this was the case with 75% of the recorded cells. The authors found the cortex to be divisible into discrete columns of cells. The cells of one column were all related to overlapping retinal areas and each had the same orientation of the axis of its receptive field. In one column cells of different eye dominance could be found. So, two cells with largely overlapping receptive fields could be of different eye dominance. It is not known whether this eye dominance is a structural characteristic of a cell or a functional one, dependent on the precise stimulus conditions. However, by means of the technique of multiple cell recording (using the same stimulus), the authors found some grouping: adjacent cells tended to be of the same ocular dominance group. It is thus possible that ocular dominance 'spreads' to adjacent areas.

In conclusion, single cells are generally summatively affected by impulses coming from the two eyes. All-or-none dominance of an eye is exceptional. Nevertheless it seems to be the rule, that for each cell one eye has a dominant effect.

In as far as these results on the cat are transferable to the human subject, the thesis of 'monocularism' has to be qualified in the sense that one eye is dominant, but not absolutely dominant for each point of the visual field. Recent experiments by Lansing (1964) showed that the EEG-response to a fluctuating left eye stimulus was reduced during periods of perceptual dominance of the right eye stimulus. But this was also no all-or-none effect: different degrees of EEG reduction were measured.

The all-or-none thesis, which is most marked in Verhoeff's paper seems therefore too simple. This is perhaps only one of this great ophthalmologist's minor mistakes (comp. Verhoeff 1964). But from Hubel and Wiesel's experiments the thesis of different degrees of eye dominance in different small parts of the binocular field may be maintained. There is furthermore no argument against a strong functional predominance along contours. In any case Hubel and Wiesel found most cell response with structured fields, and almost none when the eye was stimulated by diffuse light.

Although the assumption of different eye-dominance for each small unit of the visual field has not been sufficiently established, it has a number of theoretical advantages.

1. Binocular rivalry is promoted to the normal process in binocular

vision. It is not any more necessary to distinguish an extra 'fused state'.

2. The explanation of the existence of Panum's fusional areas becomes clear. Two lines, not falling exactly on corresponding regions of the retinas, but shifted apart by some minutes of arc are nevertheless seen as one. The extent to which this is possible determines Panum's area. But under the present assumption there is no reason any more to distinguish the case of parallel non-corresponding lines from the case of e.g. crossing lines. The 'fusion' of the lines within Panum's area may be understood as the inhibition of the line presented to one eye by the line presented to the other. If these two cases are to be ascribed to the same mechanism, the Panum area should have the same extent as the inhibitive radius of action of one contour with respect to another. This may be checked. Ogle's measurements on the horizontal extent of Panum's area (1950) give values of 6-8′ in the foveal field. That is the region within which only one line is always seen, when a binocularly disparate pair is presented. This can be compared with Kaufman's data on radius of action (see § 3), but we are now interested in the angle within which his horizontal line-segment has a predominance of 50%. A stable level of about 50% predominance was found to exist for angles within $\theta = 14'$. Half of this value is the suppressive extension in one direction. This value of 7′ accords with the extend of Panum's area.

3. The effect of binocular lustre is better understandable. Differences in dominance in small adjacent parts of the visual field cannot be perceived as long as the stimuli are identical, and as long as the law of complementary shares is valid for corresponding places at every point of the binocular field. For stimuli differing only in luminance (as for example in Exp. 2, Chapter III) such dominance differences should probably be perceptible. We did not find much evidence for this as long as the luminance difference was not too large. For large luminance differences, as e.g. the ring-and-disc pair A in Fig. 17, Chapter IV, the queer phenomenon of lustre is sometimes observed. Brightness averaging has a side-effect, which may indeed be understood as a result of the fact that the condition $w_l = w_r = \frac{1}{2}$ is not fulfilled at the micro-level of the visual field. Hering (1920) says about monocular lustre that it is caused by strong changing contrasts over a small area. This is, at least, the typical case in metallic lustre where

small spots of very high and very low luminance are intermingled. The phenomenal correspondance with binocular lustre suggests according to Hering that in the latter case small bright and dark spots are also intermingled, which accords with the assumption under concern: spots predominantly from the left eye and from the right eye are mixed. Rivalry at the micro-level, invisible in normal binocular vision, thus provokes stable lustre if luminances are sufficiently different[1].

Thinking further along these lines, a stable impression from binocularly different stimuli will only be obtained if the alternation process is reduced to the micro-level. Spread of dominance as shown by Hubel and Wiesel, will counteract this reduction process, especially along contours. For unequal contour information this hypothetical micro-level is never reached. To take this speculative argument one step further: it seems that this reduction to the micro-level takes some time. It is not only the lustre effect of Fig. 17 which takes time to stabilize, but exactly the same happens in the case of binocular colour fusion. The experiments of Thomas *et al.* (1961) show that the impression is quite labile in the first few seconds, after which a stable binocular colour may be perceived.

4. The problem of non-fusion between a border in one eye and its negative in the other eye is clarified if the assumption of 'permanent rivalry' is accepted. In observing stereoscopically Fig. 36a, a stable state immediately sets in; rivalry cannot be noticed as long as $w_l + w_r = 1$ in every point. In Fig. 36b however, a stable state cannot be obtained as long as the contours approximately coincide. In that a shift of eye dominance along some part of the contour or the whole contour will immediately be perceived. A stable state is only obtained when the contours are separated by some minutes of arc. This binocular situation is shown in Fig. 36c. In area 1, $w_l \approx 1$, because the left contour is the only border near this area (the influence of the right field is unimportant, because of its diffuse illumination). Similarly, $w_r \approx 1$ in area 3. In area 2 shifts in dominance cannot be perceived, because in both cases the field is white. Thus a stable state

[1] Still another lustre-situation is reported in the literature, namely in the metacontrast situation; this is reported by Fleischer (1939). He showed that effects of lustre arise with stimuli which also cause lustre presented binocularly. This provides another argument for the equivalency of metacontrast and binocular rivalry.

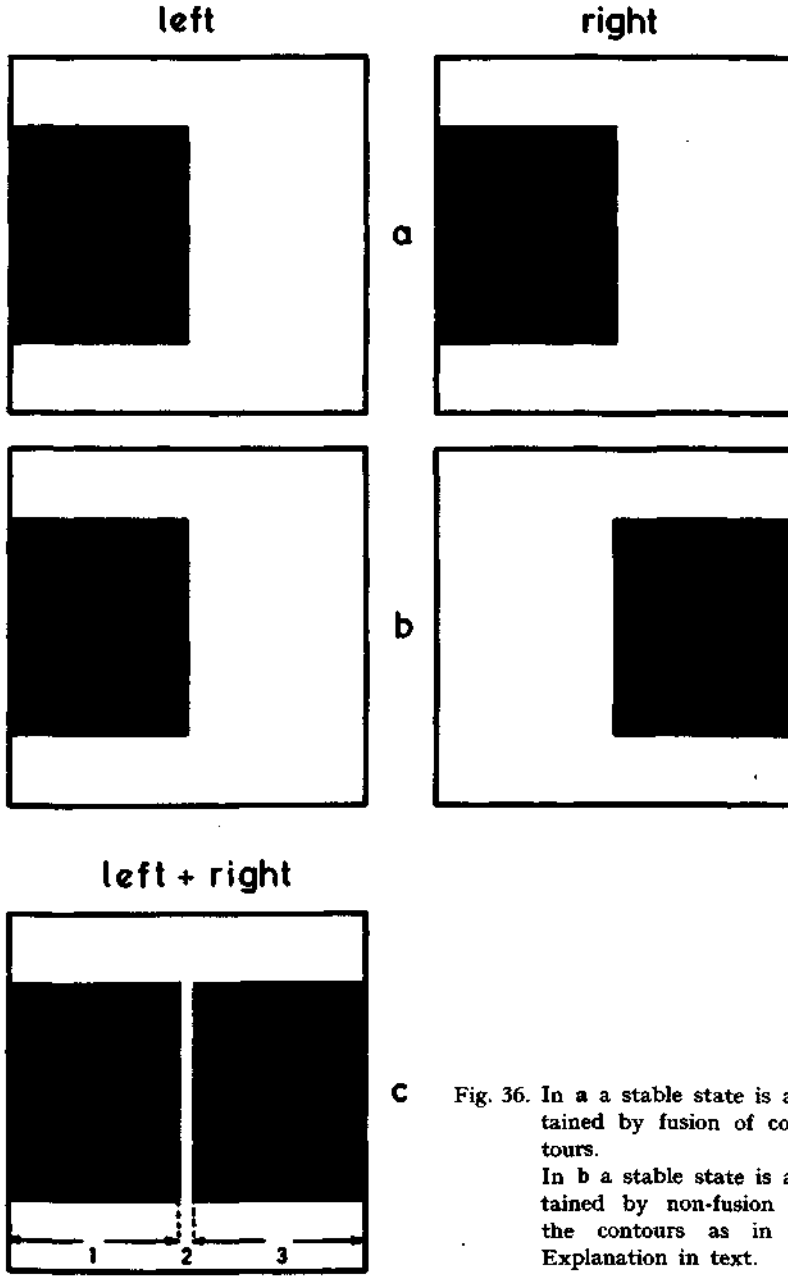


Fig. 36. In **a** a stable state is attained by fusion of contours.
In **b** a stable state is attained by non-fusion of the contours as in **c**. Explanation in text.

is only attained at the cost of the precise coincidence of contours. The same holds when the black fields overlap, instead of the white ones.

5. Lastly, the permanent rivalry hypothesis has promising advantages for an explanation of the mechanism of depth perception. Verhoeff, Asher, and Kaufman assume that, although in each point of the visual field the image from one eye is not perceived, it nevertheless contributes to the impression of depth at some other level of functioning. Hochberg (1964) goes one step further[1], in that according to him there is only one functional binocular field, the piecemeal of the contents of one eye or the other. It is interesting to study the possibility of depth perception as far as it is known, with such a cyclopean field.
But the explanation of the mechanism of depth perception has not been an objective of the present study.

[1] That rivalry and depth perception do not exclude each other was already suggested by Washburn (1931), who showed that subjects saw rivalry in free vision of a cube. The images of one and the other eye were alternatingly predominant, but solidity was permanently perceived, according to her.

SUMMARY

The subject of this study is the phenomenon which is known as *binocular rivalry*. This rivalry may arise, if the two eyes are presented with stimuli different in such a way that binocular fusion cannot occur (Chapter I). If the fields differ in contours or colours, one perceives some mosaic consisting of parts of both fields. This pattern is unstable, the images are alternatingly dominant. The dominant field of one eye seems to inhibit the field of the other eye.

The disappearance of one of these 'half-images' is not always the effect of stimulation of the other eye. Spontaneous fading, called *Troxler's effect*, may also be the cause of disappearance. Spontaneous fading is most distinct if a target is peripherally presented to the first eye, while the other eye is presented with a homogeneous field; the target seems to disappear occasionally, then. Authors discussing binocular rivalry have incorrectly attributed this phenomenon and all its derivatives to binocular interaction. The homogeneous field 'suppresses' the target, according to them. The confusion in this respect in the literature and chiefly in the study of K. Wilde is discussed in Chapter II. Because the effect is not due to binocular interaction, we called it *spurious rivalry*. The relationship of rivalry, Troxler's effect and vision with stabilized images is studied in this chapter.

The remainder of the study is devoted to 'real' rivalry. The perceptual conflict in binocular rivalry appears to be attributable to the incompatibility of two mechanisms. The first mechanism is called *binocular brightness averaging*. If the eyes are presented with identical fields of equal luminance (E_b), and one increases the luminance of the left field (up to E_l), one may keep the apparent binocular brightness constant, by decreasing simultaneously the luminance of the right field to some degree (to E_r, say). In fact, binocular brightness appears to be constant as long as a sum of weighted monocular luminances is kept constant. In formula: $w_l E_l + w_r E_r = C$, and the brightness impression is the

same as if both fields were of luminance E_b. w_l and w_r are weighting coefficients for the left and the right eye respectively, and are connected with eye-dominance (Chapter III).

Is w_l increased artificially, then w_r appears to decrease to the same amount. This is called the *law of complementary shares*. If the shares of the eyes are conceived of as proportional contributions, the law can be written as: $w_l + w_r = 1$. An artificial increase in the share of an eye can be produced by putting some contour (for instance a circle) in the field of that eye, as is shown in Chapter IV; the weighting coefficient is increased for that part of the monocular field. The smaller distance d between the fixation point and the contour, the more the weighting coefficient tends to unity. This, then, is the second mechanism, which is called the *contour mechanism*: $w \to 1$, if $d \to 0$. It is shown that this mechanism is also valid for colour contours.

That a contour 'takes its background along' can also be shown in monocular experiments. Binocular rivalry can be simulated, by presenting two different stimuli in rapid succession to the same eye (metacontrast). Instances of such 'monocular rivalry' are also given in Chapter IV.

What happens if two non-corresponding contours are presented to the eyes is discussed in Chapter V. According to the law of complementary shares $w_l + w_r = 1$, but according to the contour mechanism, we have in this situation $w_l \to 1$ and also $w_r \to 1$. The incompatibility of these two mechanisms leads to binocular rivalry. This rivalry is a 'solution' in the sense that the law of complementary shares is saved, w_l and w_r being 1 *in turn*. Furthermore a model is constructed on the basis of features of the contour mechanism, in order to describe the alternation process in time. The model is based on the fact that a foveally presented monocular contour does generally not disappear spontaneously, irrespective of its 'strength'. This leads to the suggestion that the duration of a dominance period for an eye is not dependent on the strength of the stimulus presented to that eye, but only on the stimulus strength in the other eye. Suggestions are made as to the determinants of *stimulus strength*, and some deductions from the model as to dominance times and alternation frequency are checked from the literature and by the author's own experiments. The statistical structure of the alternation model is considered. Finally this process is discussed in connection with normal binocular fusion, chiefly as regards Panum's fusional areas and the Hubel and Wiesel experiments on the visual cortex of the cat.

SAMENVATTING

Het onderwerp van deze studie is het verschijnsel dat bekend staat onder de naam *binoculaire wedstrijd*. Deze wedstrijd kan ontstaan wanneer men de twee ogen beelden aanbiedt die zodanig verschillen, dat de normale binoculaire versmelting niet kan optreden(Hoofdstuk I). Wanneer dit verschillend gecontoureerde of verschillend gekleurde velden zijn, ziet men een mozaiek bestaande uit gedeelten van beide velden. Dit patroon is niet stabiel; dan weer overweegt het ene, dan weer het andere veld. Het overheersende veld van het ene oog lijkt het veld van het andere oog te verdringen.
Het verdwijnen van een der 'halfbeelden' is echter niet altijd het gevolg van stimulatie van het andere oog. Spontaan vervagen, dat *Troxler effect* wordt genoemd kan ook de oorzaak zijn van verdwijning. Dit spontane verdwijnen is goed zichtbaar, wanneer men een lichtpunt peripheer aanbiedt aan het ene oog, terwijl men met het andere oog een homogeen veld beziet; bij tijd en wijle vervaagt en verdwijnt dan het lichtpunt. Ten onrechte hebben schrijvers over binoculaire wedstrijd dit verschijnsel in al zijn vormen toegeschreven aan binoculaire interactie. Het lichtpunt zou worden 'uitgedoofd' door het homogene veld voor het andere oog, volgens hen. In Hoofdstuk II wordt de verwarring die dit in de literatuur, en met name in het werk van K. Wilde teweeg heeft gebracht ontrafeld. Omdat het effect niet ontstaat door binoculaire interactie, noemden we het *schijnbare wedstrijd*. Het verband tussen wedstrijd, Troxler effect en zien met gestabiliseerde beelden wordt in dit hoofdstuk onderzocht.
In de rest van het proefschrift wordt de 'echte' wedstrijd bestudeerd. Het waarnemingsconflict blijkt te kunnen worden teruggevoerd op de onderlinge onverenigbaarheid van twee mechanismen. Het eerste mechanisme werd genoemd *binoculaire helderheidsmiddeling*. Wanneer men de twee ogen corresponderende velden aanbiedt van gelijke helderheid (E_b), en men verhoogt nu de helderheid van het linker veld

(tot E_l), dan kan men de waargenomen helderheid constant houden door tegelijk de helderheid voor het rechter oog te verlagen tot een zekere waarde (stel: tot E_r). In feite blijkt de waargenomen helderheid constant te zijn zolang een gewogen som van de monoculaire helderheden constant wordt gehouden. In formule: $w_l E_l + w_r E_r = C$, en de helderheidsindruk is dan hetzelfde als wanneer beide monoculaire velden de helderheid E_b bezaten. w_l en w_r zijn wegingscoefficienten voor respectievelijk het linker en het rechter oog, en hebben met oogdominantie te maken.
Vergroot men kunstmatig w_l, dan verkleint w_r in dezelfde mate. Dit werd de *wet van complementaire aandelen* genoemd. Als de aandelen der ogen worden beschouwd als proportionele bijdragen, dan kan deze wet worden geschreven als $w_l + w_r = 1$. Zo'n kunstmatige toename van het aandeel van een oog kan worden teweeg gebracht door in het veld van het betreffende oog een contour aan te brengen (bv. een cirkeltje). De wegingscoefficient wordt dan voor dat gedeelte van het monoculaire veld verhoogd. Dit wordt in Hoofdstuk IV aangetoond. Hoe kleiner de afstand d tussen fixatiepunt en contour, hoe dichter de wegingscoefficient tot 1 nadert. Dit is het tweede mechanisme dat *contour mechanisme* werd genoemd: $w \to 1$, als $d \to 0$. Aangetoond wordt dat dit mechanisme ook functioneert voor kleurcontouren.
Het verschijnsel dat een contour zijn achtergrond 'meeneemt' is ook aantoonbaar door middel van monoculaire proeven. Binoculaire wedstrijd blijkt te kunnen worden gesimuleerd, door de twee beelden snel achtereen aan één oog aan te bieden (metacontrast).
In Hoofdstuk V wordt beschreven wat er nu gebeurt wanneer men niet-corresponderende contouren aan de twee ogen aanbiedt. Volgens de wet van complementaire aandelen is $w_l + w_r = 1$; volgens het contourmechanisme krijgen we in deze situatie $w_l \to 1$ en ook $w_r \to 1$. De onverenigbaarheid van deze mechanismen leidt nu tot binoculaire wedstrijd. De wedstrijd is een 'oplossing' in die zin, dat de wet van complementaire aandelen gespaard blijft doordat w_l en w_r *om beurten* gelijk worden aan 1. Verder wordt in dit hoofdstuk uit eigenschappen van het contour mechanisme een model ontwikkeld dat een beschrijving kan geven van dit afwisselingsproces in de tijd. Het model is gebaseerd op de constatering dat een monoculair foveaal aangeboden contour nooit spontaan verdwijnt, onafhankelijk van zijn 'sterkte', doch slechts door een contour in het andere oog aan te bieden. Dit leidt tot de stelling dat de duur van de dominantieperiode van een prikkel in het ene oog, niet afhankelijk is van de eigen prikkelsterkte,

doch slechts van de prikkelsterkte in het andere oog. Determinanten van de *prikkelsterkte* worden voorlopig omschreven en enkele gevolgtrekkingen uit het model met betrekking tot dominantietijden en afwisselingsfrequenties worden aan de literatuur en aan eigen experimenten getoetst. Tevens wordt de statistische structuur van het afwisselingsproces in beschouwing genomen. Tot slot wordt dit proces in verband gebracht met normale binoculaire versmelting, voornamelijk met betrekking tot Panumse versmeltingvelden en de experimenten van Hubel en Wiesel op de visuele cortex van de kat.

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STELLINGEN

1. Het schijnbaar verdwijnen van een monoculair aangeboden contour (het Troxler effect) bij homogene stimulatie van het andere oog is door veel schrijvers, met name door K. Wilde, ten onrechte toegeschreven aan binoculaire interactie.
   Lit. K. Wilde, Psychol. Forsch., 1938, *22*, 26 - 58.

2. In tegenstelling tot de Gestaltpsychologische stelling blijkt zowel bij het tot stand komen van de diepte-impressie als bij binoculaire rivaliteit de binoculaire interactie de Gestaltvorming functioneel vooraf te gaan.

3. Bij het alterneren van twee indrukken in binoculaire wedstrijd is de gemiddelde duur tijdens welke een indruk uit een oog dominant is slechts afhankelijk van de prikkelsterkte in het contralaterale oog.

4. De mens is tot op zekere hoogte in staat te discrimineren welk van zijn ogen gestimuleerd wordt; dit blijkt uit onderzoeken van Pickersgill en van Van der Geer en Moraal. Hochberg concludeert uit het eerste onderzoek ten onrechte het tegendeel.
   Lit. M. J. Pickersgill, Quart. J. exp. Psychol., 1961, *13*, 168 - 172.
   J. P. van de Geer & J. Moraal, Report I.Z.F. 1963-5.
   J. Hochberg, Percept. mot. Skills, 1964, *19*, 685.

5. Bij microarbeid make men geen gebruik van binoculaire microscopen met slechts één objectief (waarbij zg. 'pseudostereoscopie' optreedt).

6. Oorspronkelijke causale indrukken in de zin van Michotte (wegstoten en meenemen) en afgeleide (bv. remming) kunnen worden onderscheiden doordat stimulus-variatie in het eerste geval de inhoud van de causale antwoorden verandert, doch in het tweede geval slechts de relatieve frequentie ervan.

7. Mensen zonder speciale muzikale scholing gebruiken het begrip 'consonantie' in evaluatieve zin. Zij duiden daar in de eerste plaats tertsen en sexten mee aan; dit in afwijking van het musicologische begrip, dat evaluatief neutraal is en prime, octaaf, kwint en kwart aanduidt.

8. De consonantiegraad (in evaluatieve zin) van een tweeklank is niet alleen van cultuurhistorische factoren afhankelijk, maar ook van de struktuur van het gehoororgaan; dit blijkt onder meer uit het feit dat tweeklanken die dissonant worden ervaren wanneer zij gemengd binauraal worden aangeboden, dit dissonante karakter verliezen wanneer een van de tonen aan het ene oor wordt aangeboden en de andere aan het andere oor.

9. Het binnenvaren in een sluis door een duwconvooi kan voor de kapitein worden vergemakkelijkt door de remmingwerken symmetrisch ten opzichte van de sluisas te leggen, en door deze werken een zo gering mogelijk verloop te geven.

10. Adekwate adviezen met betrekking tot de steeds frequenter voorkomende artificiële waarnemingssituaties in industrie en elders zijn vaak mogelijk dank zij reeds voorhanden laboratorium-gegevens over de relevante zintuiglijke processen.

11. Door gebrek aan communicatie tussen internaten is bij wisseling van tehuis voor de intern geen continuiteit van pedagogische aanpak gegarandeerd.

12. Het verontrustende resultaat van een recente enquête over de houding van de Nederlander tegenover het Parlement kan een artefakt zijn van de aanvechtbare wijze waarop het nulpunt van de gebruikte attitude-schaal is bepaald (de zg. 'fold-over'-techniek).
Lit. M. Zeldenrust-Noordanus, I.P.M.-rapport. Jan. '65.

13. De in Nederland veel voorkomende mening dat psychologen zich bij uitstek bezig houden met het onderkennen van individuele verschillen is een 'self-fulfilling prophecy' in de zin van Merton; zij komt de ontplooiing van andere deelgebieden der psychologie niet ten goede.

Stellingen behorende bij het proefschrift van W. J. M. Levelt,
On Binocular Rivalry,
Leiden 1965